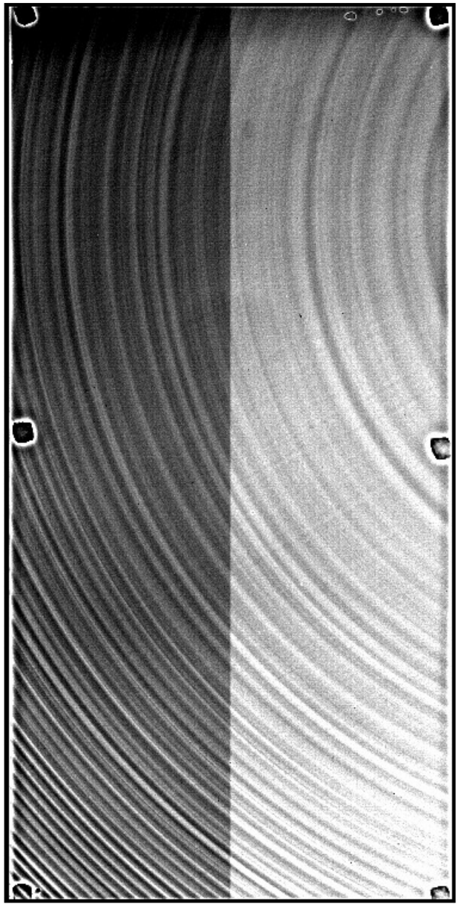
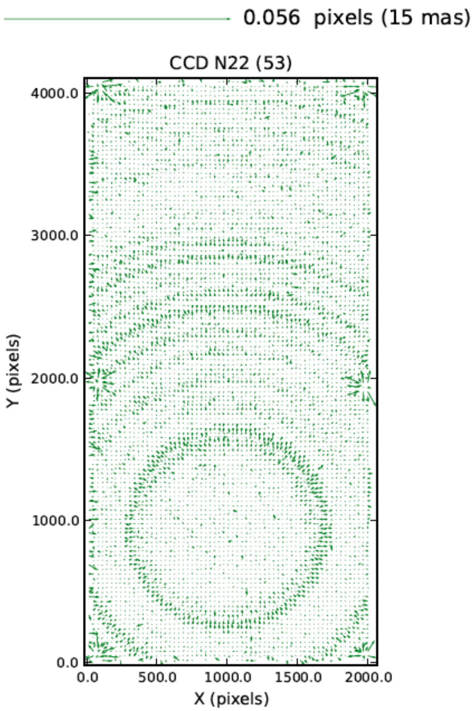
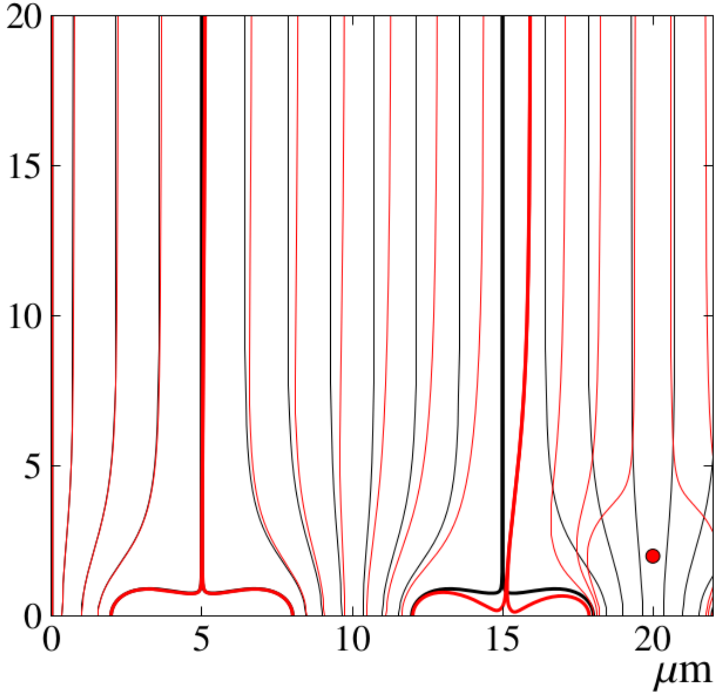
Precision Astronomy with Deep-Depleted CCDs
(BNL 4-5/12/2014)

Introduction







Pierre Astier
LPNHE / IN2P3 / CNRS , Universités Paris 6&7.

PACCD (2013)

The workshop was triggered by observations of "strange things" , when using CCDs:

- *Tree-rings* in flat-fields
- The *brighter-fatter* effect (aka "fat PSF")
- Correlation in flatfields/ non-linear PTC
- Response "roll-off" on sensor edges
- ….

… which seemed related to deep-depleted CCDs

→ Let us share our experiences !

Outline

I'll go (rapidly) through the various effects and try to summarize (maybe brutally) what was shown last year.

I'll discuss rapidly some issues related to "flatfielding"

I will not quote all presentations from 2013 !

PACCD : my recollection of 2013

- Tree rings are there, but their scale varies with brand and batch.
- All reported attempts to observe the brighter-fatter effect did succeed (E2V E250, ITL, DECam, HSC, MegaCam, SDSS spectrograph ...)
- All attempts to observe correlations in flatfields did succeed.
- Rapid change of the sensor response on edges is present at various scales on thick CCDs

PACCD (2013)

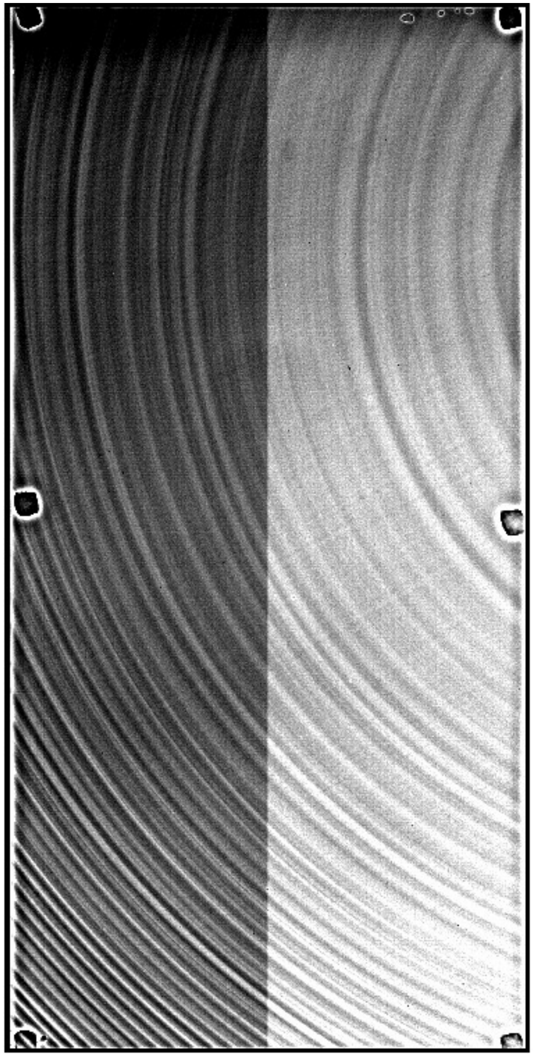
These effects have likely always been present in CCDs

They are just stronger in deep-depleted CCDs

(C. Stubbs, my words)

“Tree rings” (2103)

Structures on the flat

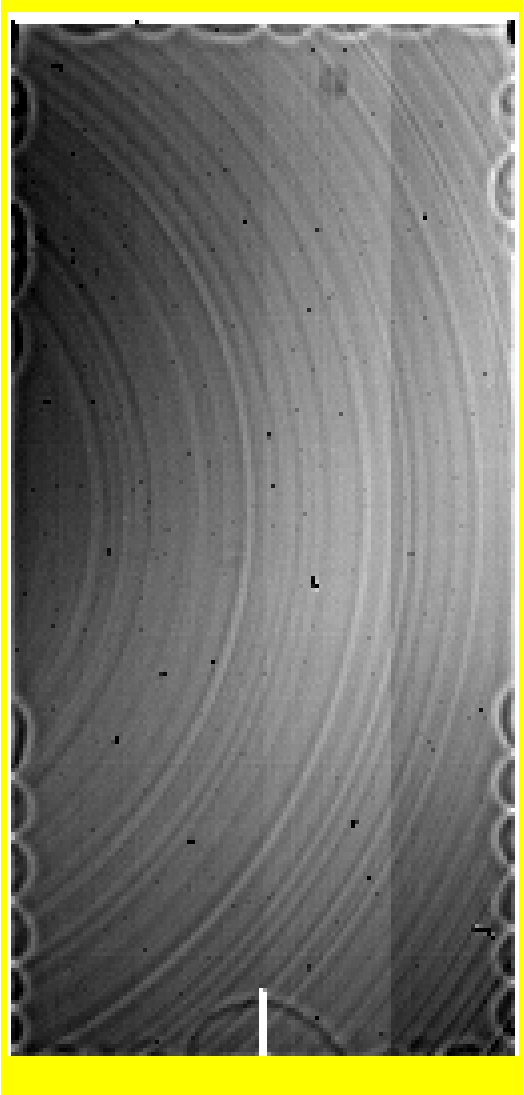


DES findings:

- Amplitude : ~ 0.4 % peak-to-peak.
- Same pattern in all bands
- The bluer the stronger : g ~ 2*Y
- Affects photometry and astrometry

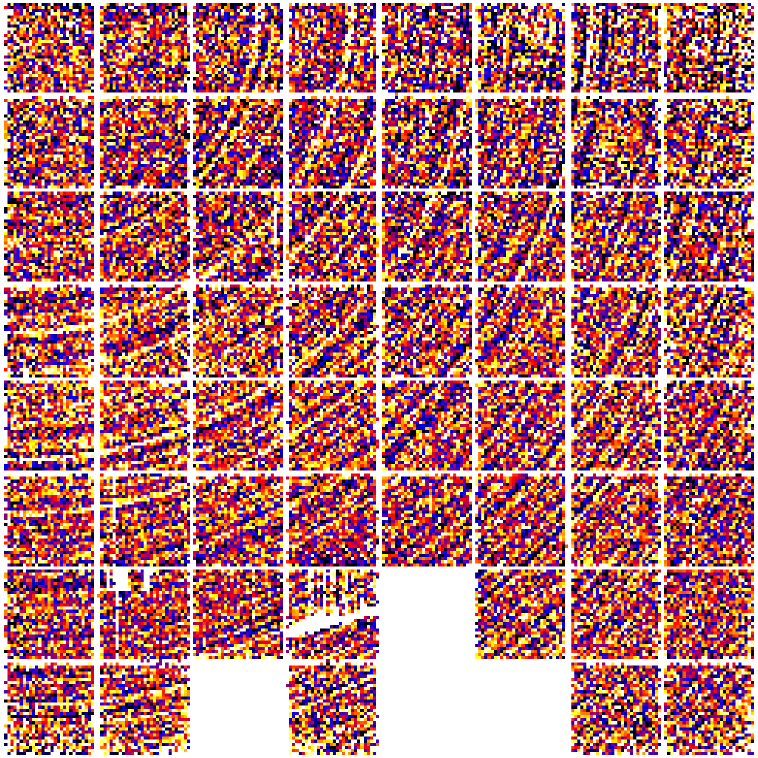
A.A. Plazas Malagón/ G. Bernstein

Tree rings (2013)



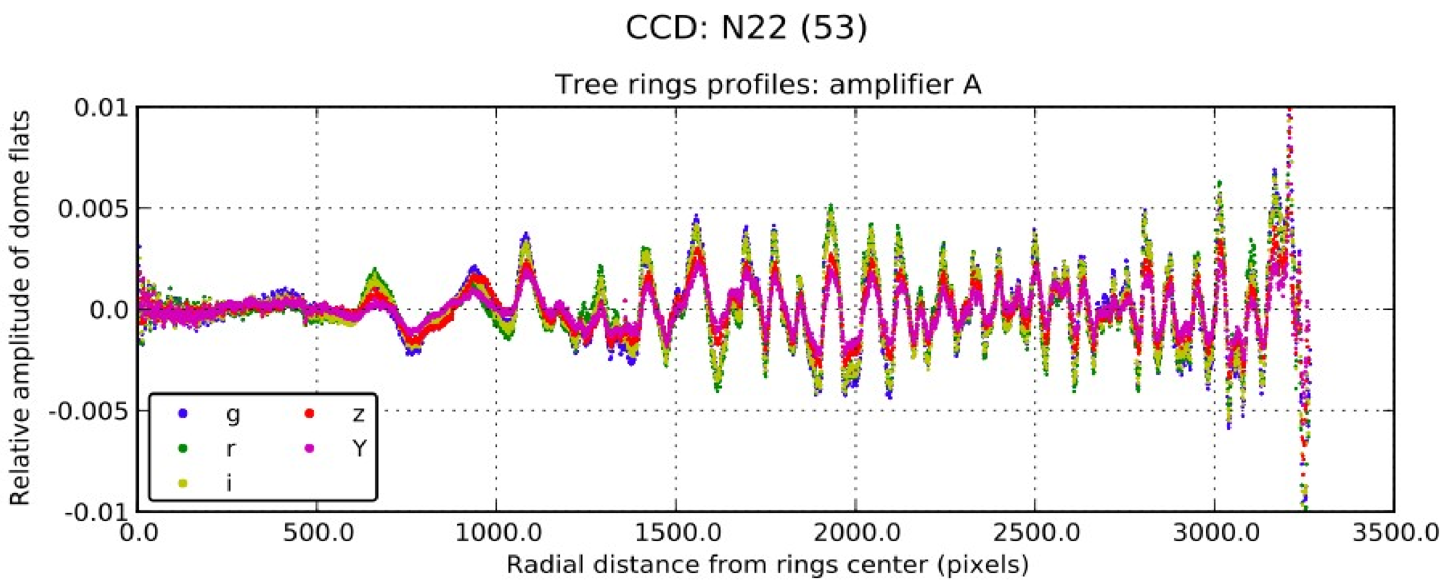
HSC find similar patterns
and amplitudes (R. Lupton)

Pan-STARRS (E. Magnier)



Tree rings (2013)

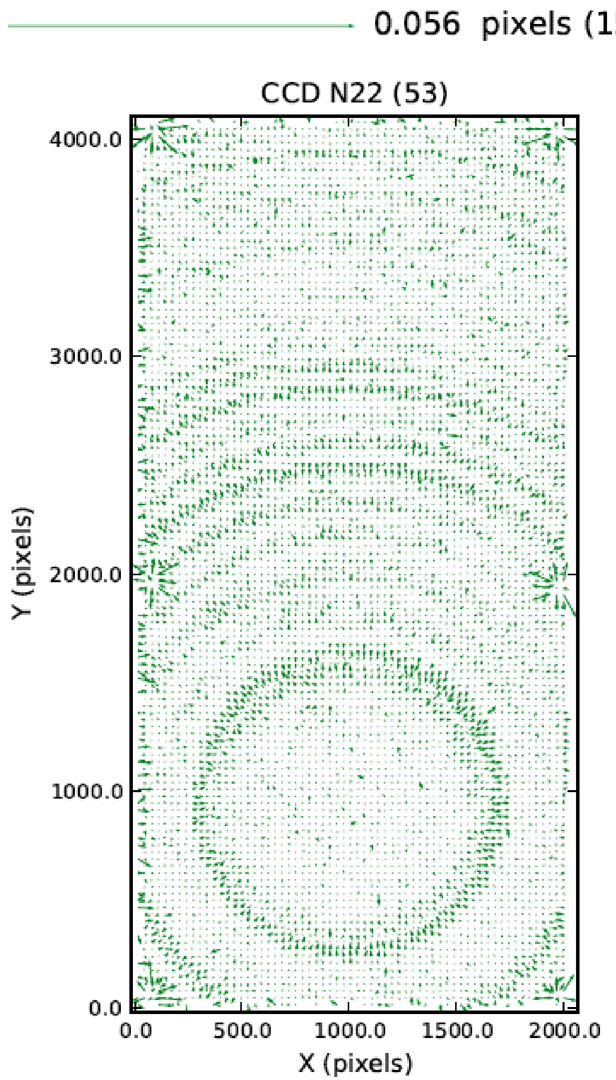
DECam flats : cut "perpendicular" to rings



Note the chromatic dependence

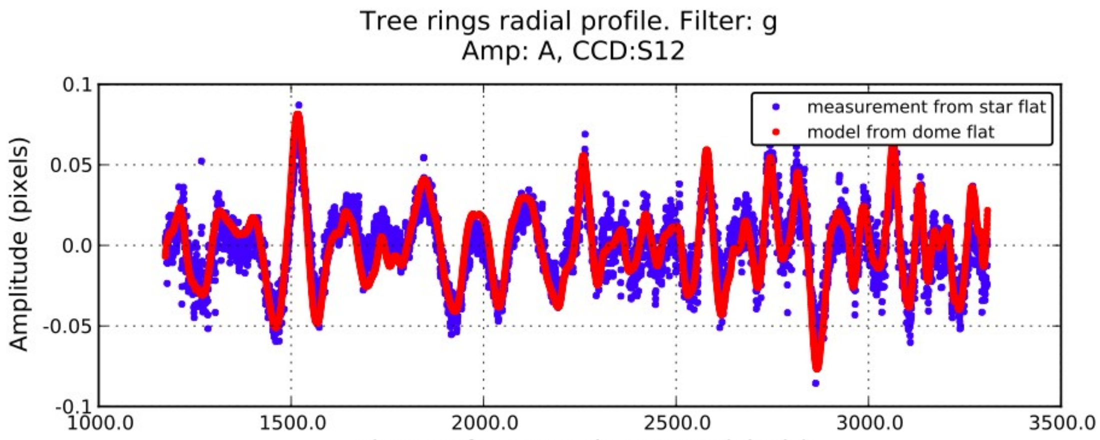
A.A. Plazas Malagón (2013)

Tree rings (2013)



Averaged astrometric residuals

Comparison of measured astrometric residuals to their expectation from flats:



Nice, isn't it ?

A.A. Plazas Malagón

Tree rings (my take)

- Pretty convincing case that static transverse fields are at play (likely induced by doping inhomogeneities)
- They cause an image displacement (like lensing on CMB)
- This displacement ~~messes up~~ challenges astrometry
- The gradient of the displacement distorts the star shapes ....
- … and contributes apparent shear

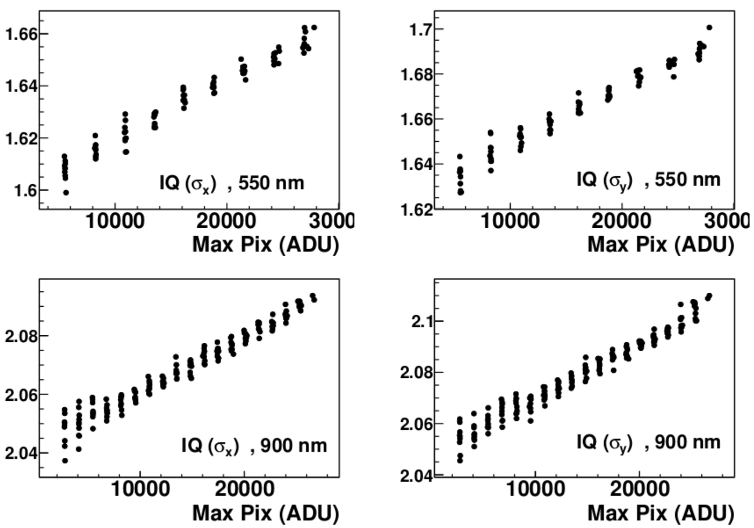
Tree rings (my take)

We should measure the displacement field.

- Stacking astrometric residuals ? Currently our best hope.
- Using the flats?
  - The flat is sensitive to these transverse fields.
  - The flat is a scalar, the displacement is a two-component vector.
  - The flat is also affected by QE variations.
- I don't know of any proposal that the displacement field follows some local constraint (e.g. gradient of some poetential)
- General recipe still to be proposed (unlikely to rely only on flats)

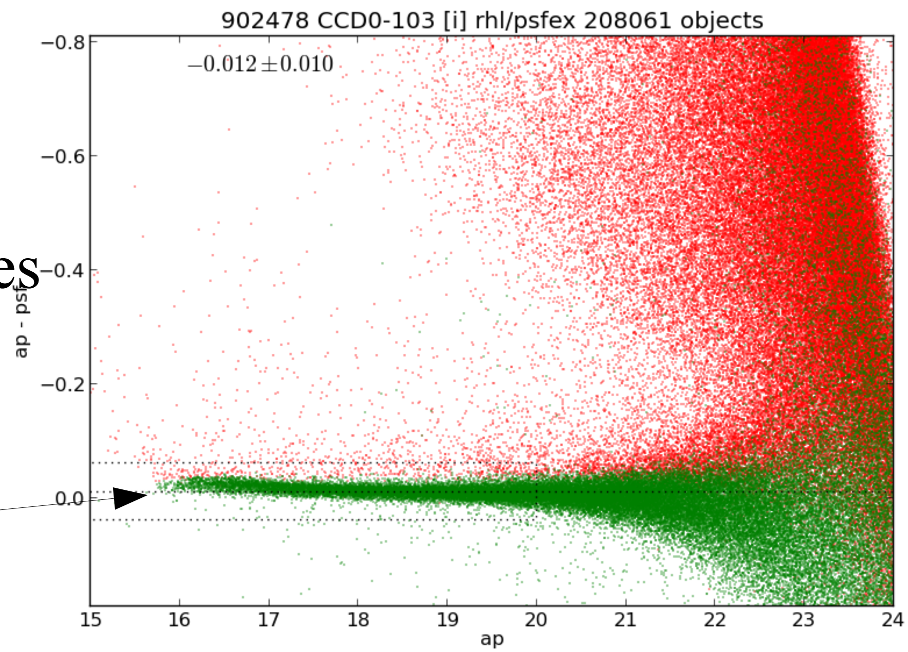
Brighter-fatter (2013)

Two examples among many more):



Spot sizes as a function of their peak brightness
LSST/E2V (P.A. et al)

PSF-aperture magnitudes
HSC (R.Lupton)



stars

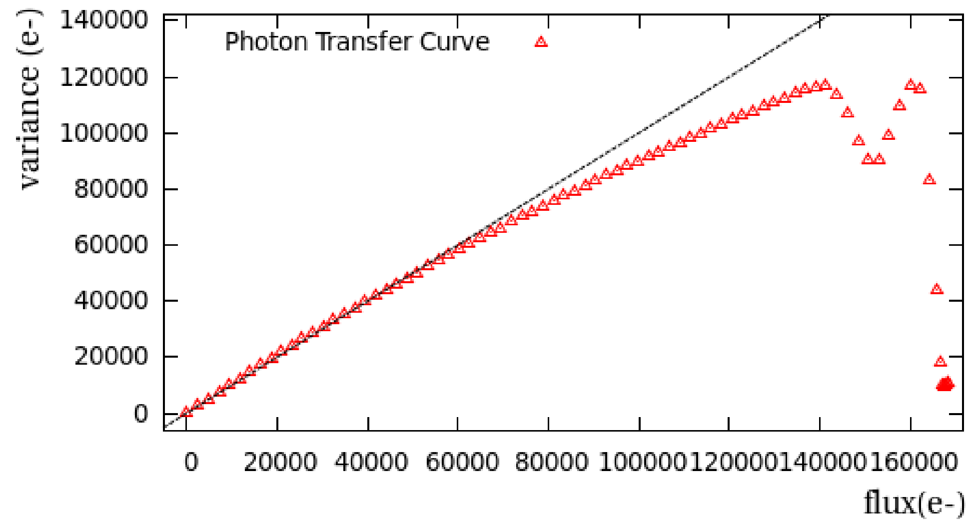
Brighter-fatter (2013)

- Found on DECam, LSST candidates, Megacam, HSC, ….
- The increase in size can reach a few %.
- At this kind of level, large scale weak lensing projects cannot ignore the effect (M. Jarvis)
- Anisotropy: we seem to find that the increase is larger along rows than along columns (~ 20 %)

Correlations (2013)

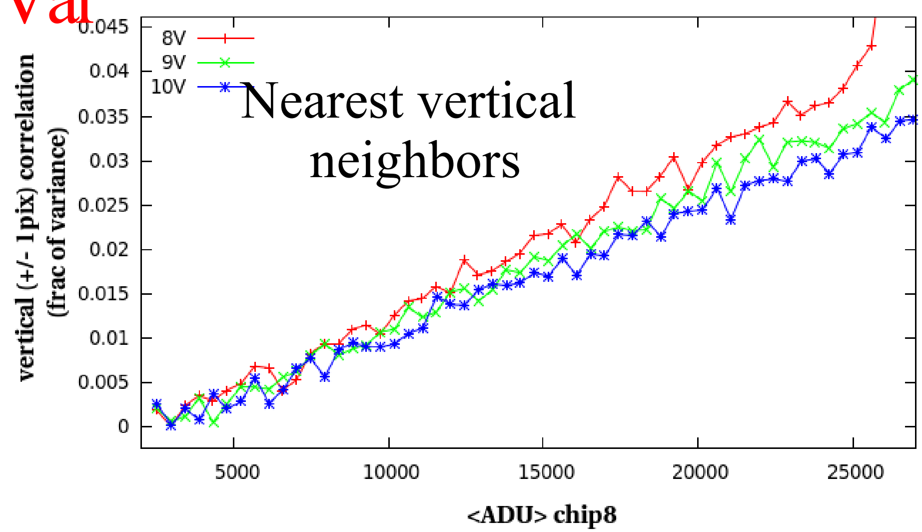
The BF effect might be related to to other non-linear phenomena:

Variance of flatfields increases less rapidly than their average.



Cov/Var

There are pixel correlations in flatfields, linearly increasing with the average.



Average

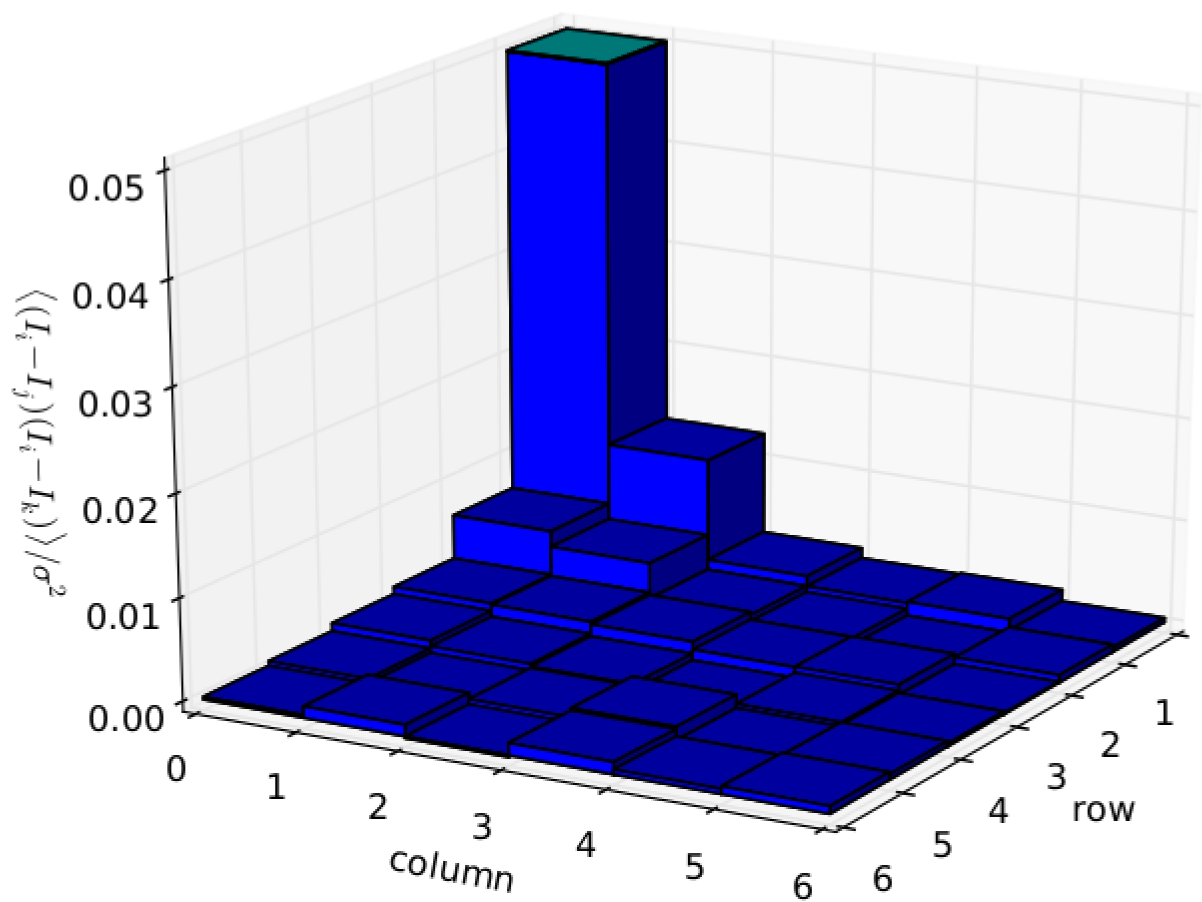
(Doherty/Guyonnet)

Correlations (2013)

HSC : these correlations are anisotropic and decay with separation

(R. Lupton)

Similar pattern on DECam, LSST Candidates, Megacam and earlier publications



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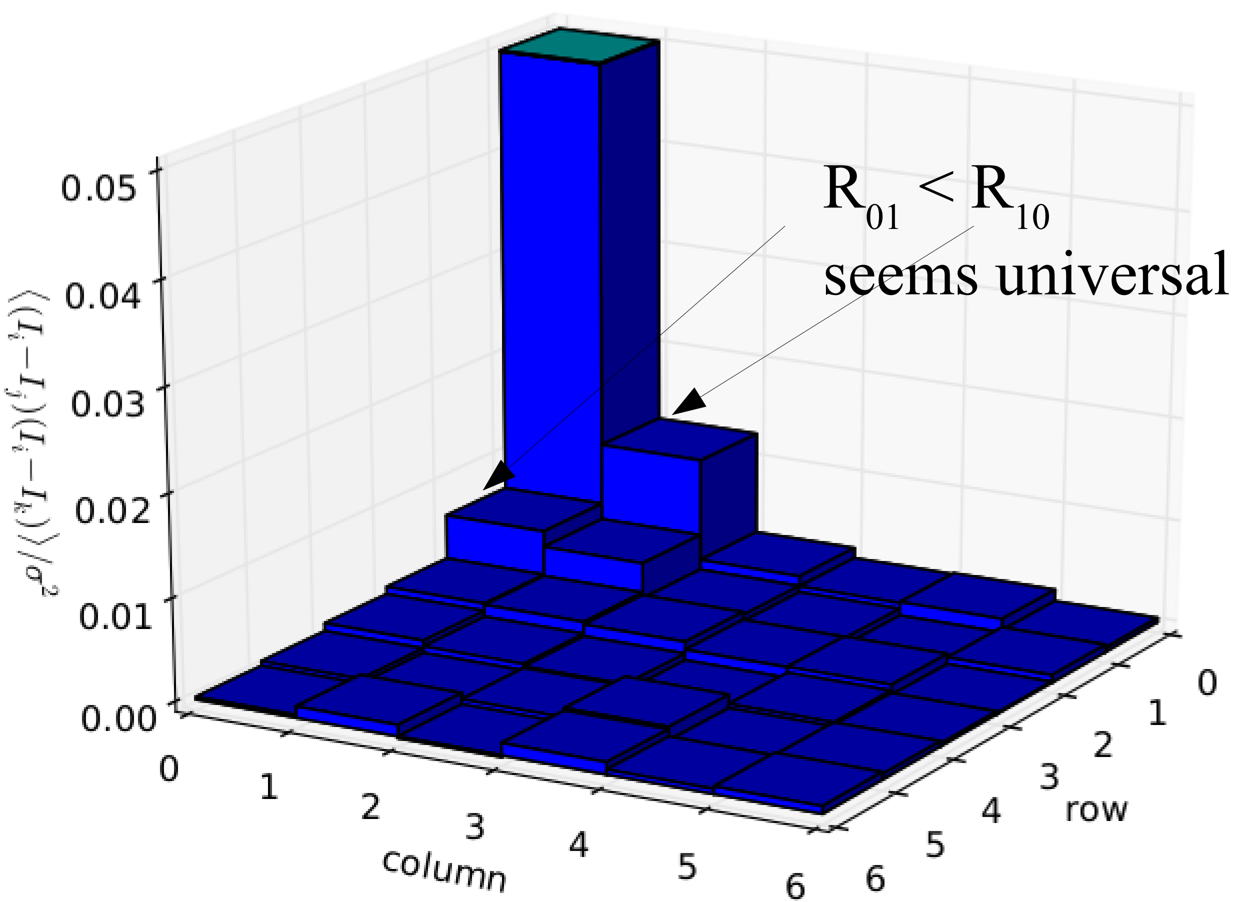
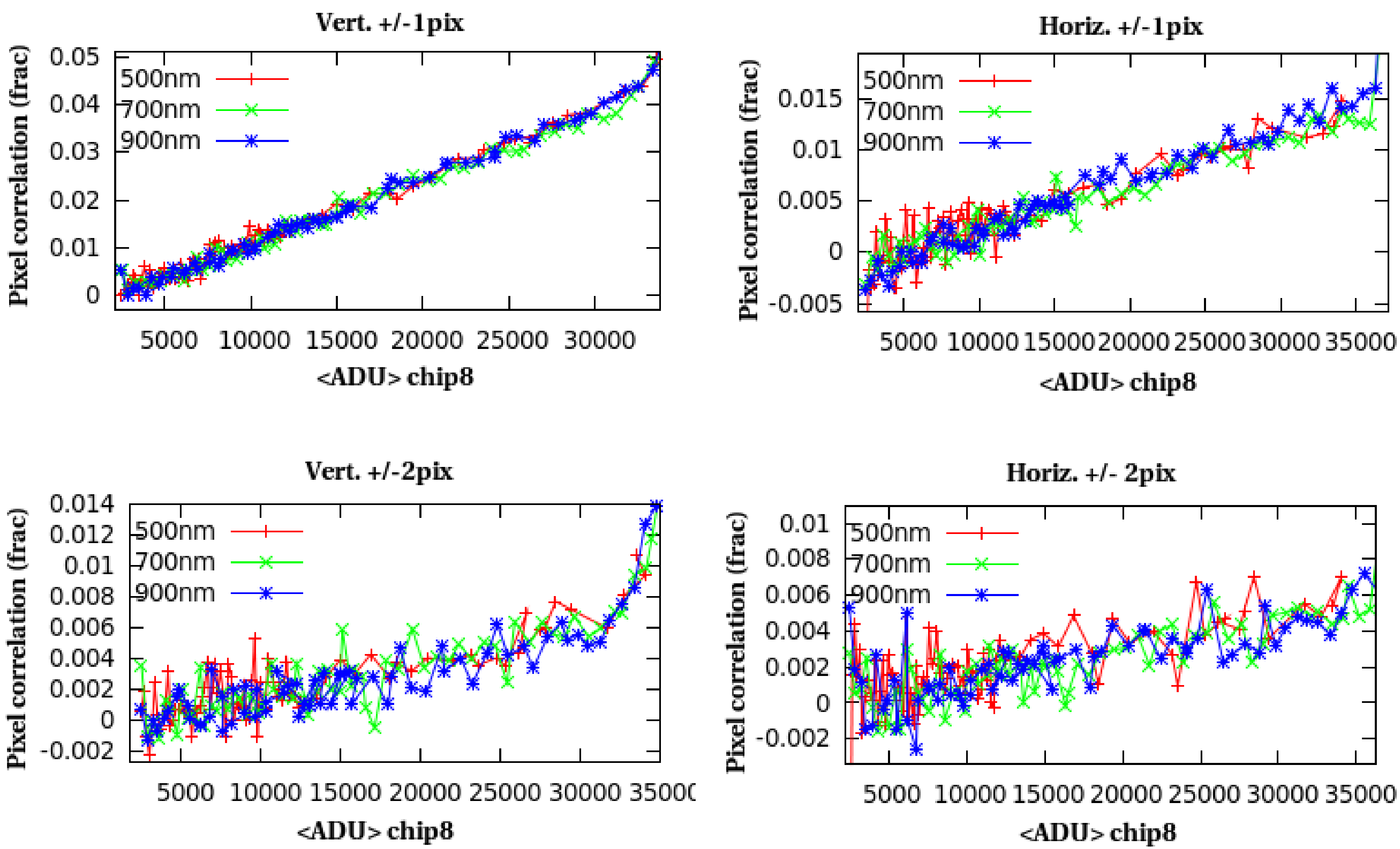


Correlations look achromatic (2013)



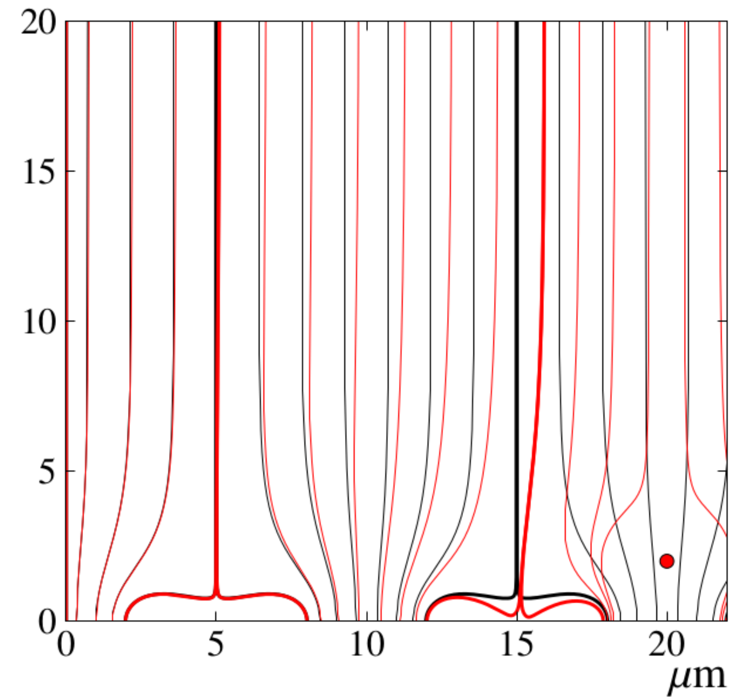
(Doherty/Guyonnet)

Brighter-fatter/correlations (2013)

- The rising correlations and flattening PTC are trivially related.
- We can check that the "missing variance" in the PTC matches the measured correlations (A. Guyonnet, tomorrow).

Are the correlations and the brighter-fatter effect different manifestations of the same physics?

- Probably (P.A, last year)
- More on this by D. Gruen, A. Guyonnet, …?



So: 2 classes of “imaging” distortions

- Static distortions:
  - Tree rings
  - Edge distortions (roll-off or blooming)
- Dynamic distortions:
  - Brighter-fatter
  - Correlations

So: 2 classes of “imaging” distortions

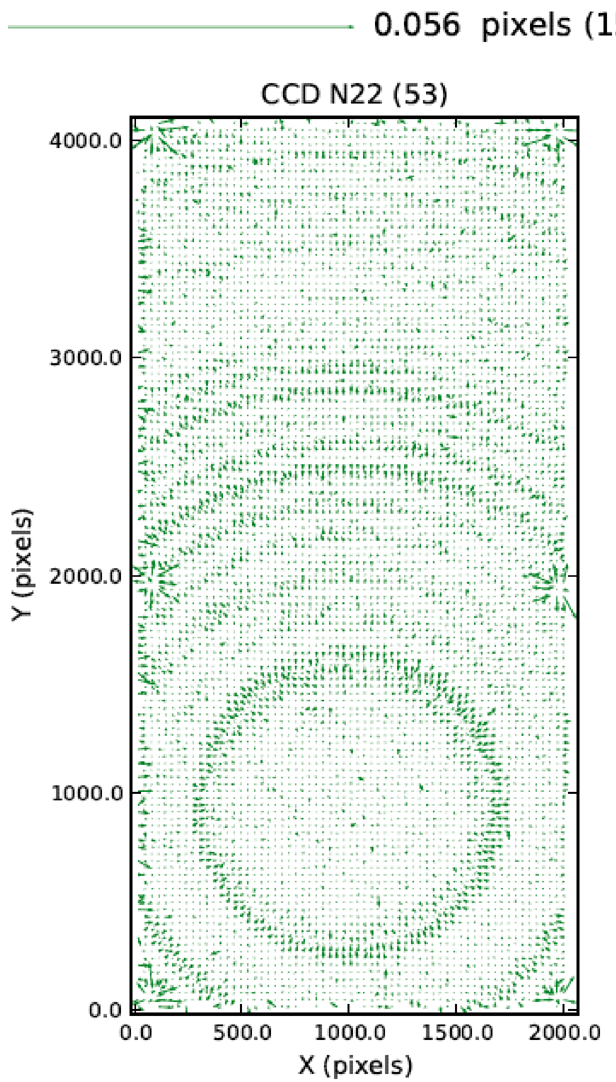
- Static distortions: $\leftarrow$ chromatic
  - Tree rings
  - Edge distortions (roll-off or blooming)
- Dynamic distortions: $\leftarrow \sim$ achromatic
  - Brighter-fatter
  - Correlations

Mapping static distortions

- Average astrometric residuals
  - Requires specific observing strategy?
  - Precision ?
  - No specific hardware required.
- Rely on the flat only ??
  - Requires some assumption to extract the displacement field (2D) from the flat (scalar)
  - Separation from genuine QE variations ?

Mapping static distortions

Induce a “displacement field”



$$X_{bottom} = X_{top} + \delta$$

Uniform illumination $$F' \simeq F[1 - div(\delta)]$$

General illumination $$P' = P[1 - div(\delta)] - \nabla P.\delta$$

Accounting for QE : we observe EP'

$$EP' = EP[1 - div(\delta)] - E\nabla P.\delta$$

- Need several “P”'s to solve for “δ” and “E”
- Known patterns ??
- Simple patterns to be fitted ?
- Simpler than brute force astrometry?
- We'll hear about proposals here

Flatfielding : what for ?

- Obtain a uniform photometric response ?
  - Varying plate scale issues
  - Tree rings & co
  - Non uniform filters
  - ….
- Obtain a ~ flat sky, for sky subtraction !
  - Restore photometric uniformity on catalogs
  - Model PSF and shapes using undistorted coordinates

Flatfielding

Once the sky is essentially flat on small scales :

- Aperture fluxes
  - Should be corrected (e.g Bernstein PACCD 2013)
- PSF modeling
  - Should account for the distorted pixel grid and applied flat-fielding.
- Shape measurements
  - Should account for the distorted pixel grid.

Flatfielding from uniform illuminations

Image corrector:

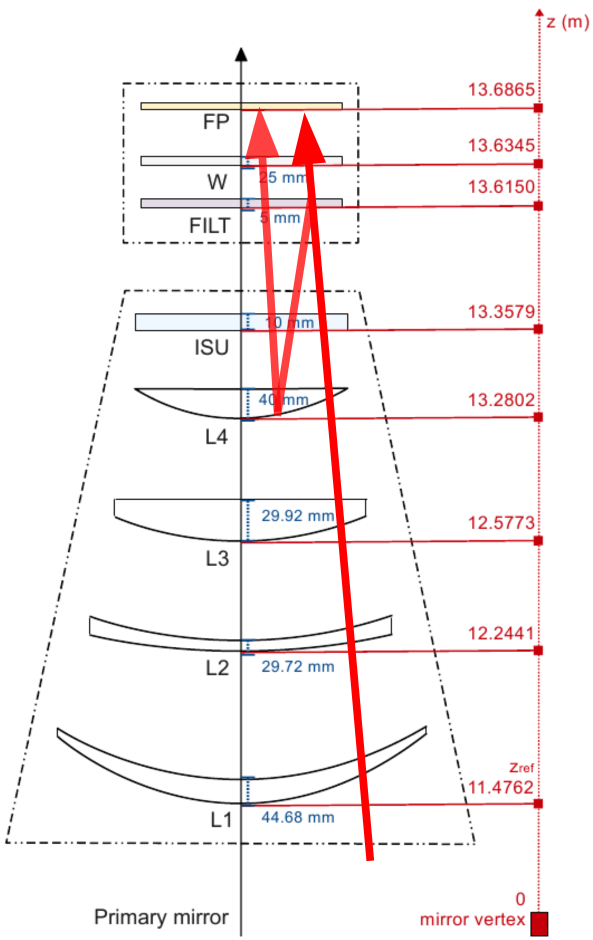
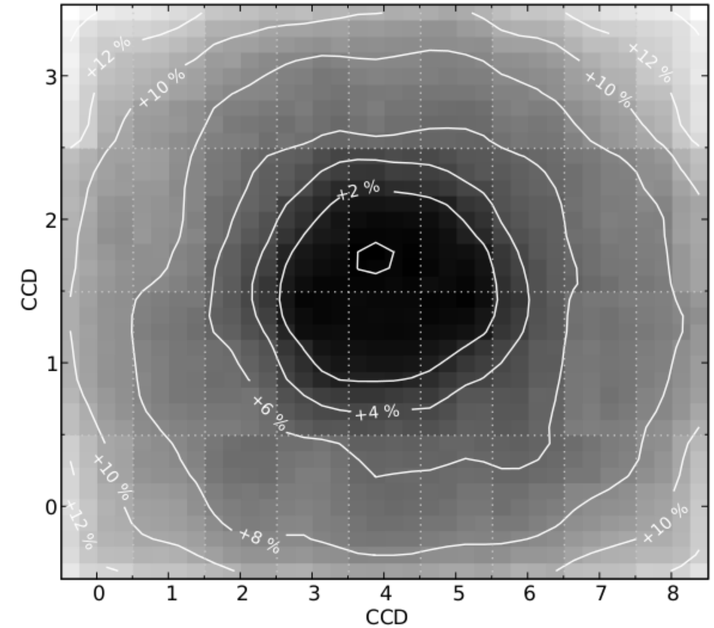


Image correctors generate ghosts, which contribute to flatfields.

On large scales, a photometric correction of catalogs is needed anyway.

Megacam:
a 12 % correction
in the corners

(Regnault et al, 2009, Betoule et al 2013)

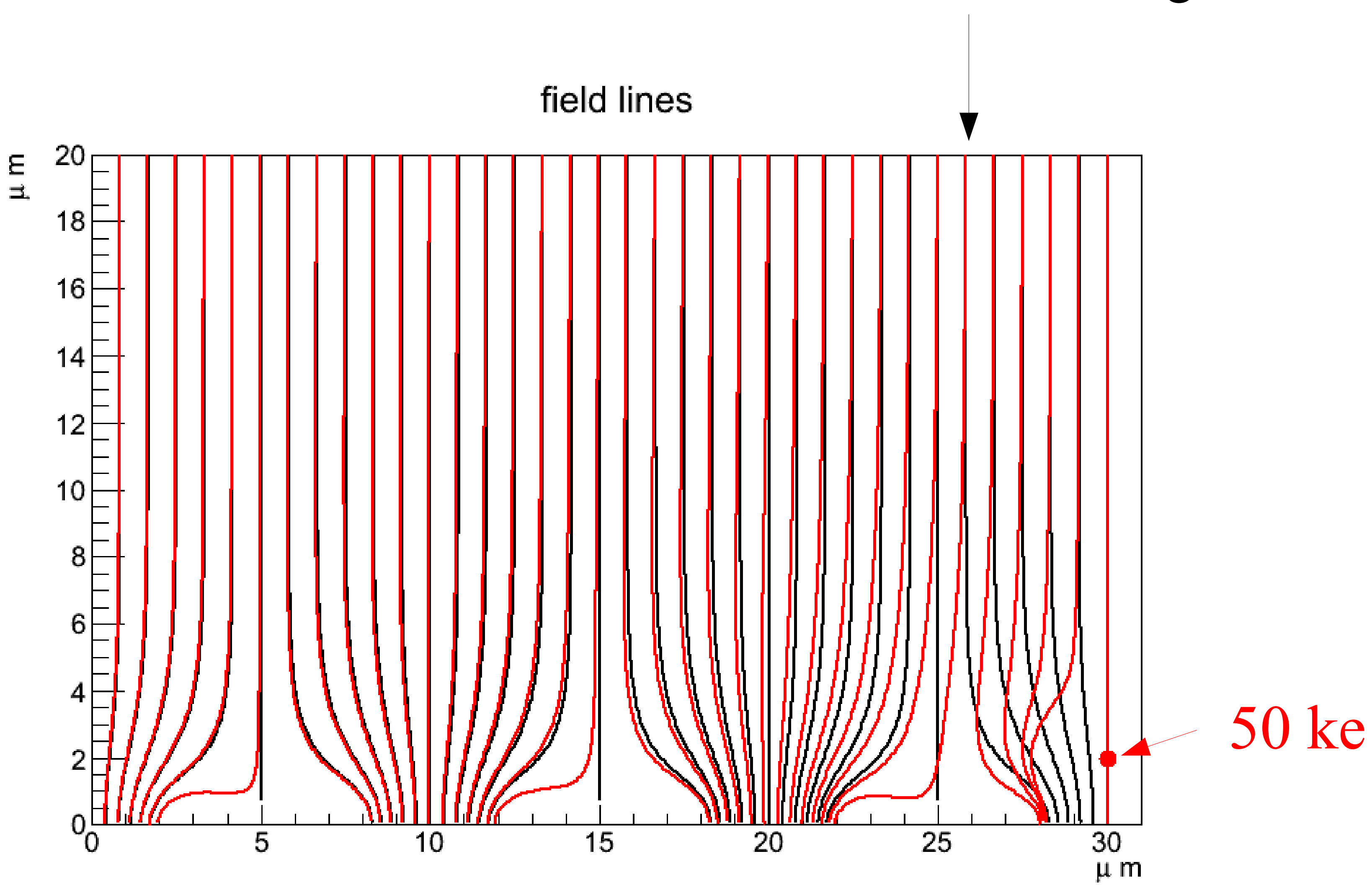


Flatfielding *is* tricky

- Even with perfect sensors & perfect filters
- Static distortions in CCDs are “just” one extra set of complications
- Flatfielding choices should consider seriously the quality of sky subtraction
- Catalogs will probably have to be post-processed anyways
- Flatfielding becomes event more tricky with spatially-variable filters......

Dynamic distortions

Depending on the stored charge, electrons drifting here turn left or right



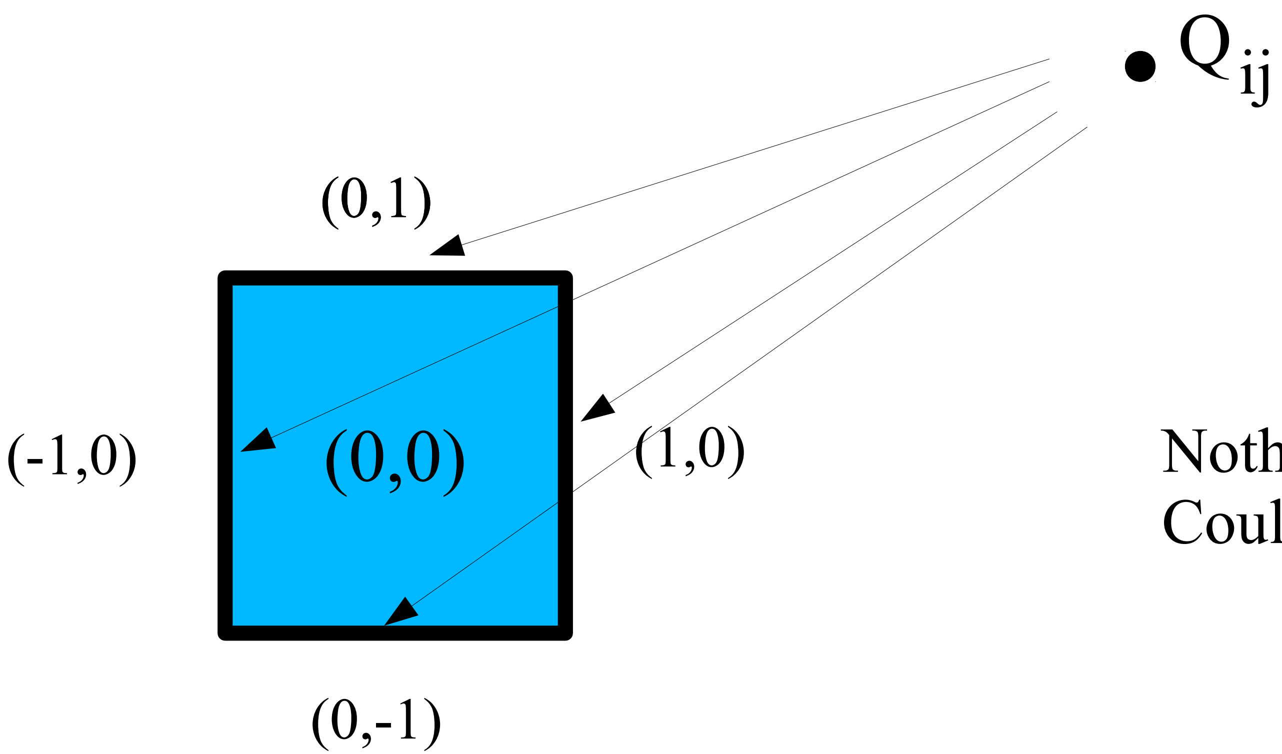
Mapping dynamic distortions

- The stored charge pattern distorts the average drift lines
- It also decreases the drift electric field, and hence increases lateral diffusion (S. Holland).
- Both effects are at play
- We can compute both and compare (A. Guyonnet)
- Remember that the effects we see are mostly achromatic → diffusion mechanisms are marginal

A simplistic physical model

- Charges stored in a CCD source an electric field
- Drift trajectories are perturbed by this additional electric field
- Pixels boundaries are affected by these perturbations.

$\rightarrow$ Effective pixel boundaries are (marginally) dynamical



Nothing but
Coulomb forces !

Assuming that boundary displacements are linear w.r.t source charges:

$$\boxed{\delta Q_{0,0} = \frac{1}{4} \sum_X \sum_{i,j} a_{ij}^X Q_{ij} (Q_X + Q_{00})}$$

To be determined:
Characteristic of a device
(+ operating conditions)

Source charge

Test charge.
<u>Assumes the image is well sampled.</u>

It turns out that the influence of increased lateral diffusion has the same form.
So, empirical "a" coefficients capture perturbations of both lateral and longitudinal electric fields.

Correlations in flats

$$Q'_{0,0} = Q_{00} + \sum_X \sum_{ij} a_{ij}^X Q_{ij} (Q_{00} + Q_X)$$

For a flat-field (average μ, variance V) one gets :

$$Cov(Q'_{00}, Q'_{ij}) = \mu V \sum_X a_{ij}^X$$

Sum over 4 sides

So :
- correlations (Cov/V) increase linearly with illumination
- variance of flat-fields : Poisson term minus a quadratic correction

Mapping dynamic distortions

- Map those using correlations in flats
  - Under-constrained in the general case (see A. Guyonnet, D. Gruen)
  - $\rightarrow$ have to rely on some smoothness hypothesis
  - Is it precise enough ?
- Electrostatic computations (A. Connolly, ...)
  - We do not know as much as we would like …
  - Are we immune to the unknowns ?
- We need an accurate measurement of response non-linearity

Conclusions/summary : what I hope to learn about

- Static distortions:
  - Astrometric residuals (?)
  - Artificial (non-flat) patterns
- Dynamic distortions
  - Flat correlations + smoothness constraints
  - Full 3-D electrostatics
- Photometric calibration
- Shear measurements
- Surprises

More slides

Our definition for the size of stars

- We use Gaussian-weighted second moments

We solve these equations for M_g: $\quad M_g \equiv \begin{pmatrix} m_{xx} & m_{xy} \\ m_{xy} & m_{yy} \end{pmatrix}$

$$\boldsymbol{M}_g = 2\frac{\sum_{pixels}(\boldsymbol{x}_i - \boldsymbol{x}_c)(\boldsymbol{x}_i - \boldsymbol{x}_c)^T W_g(\boldsymbol{x}_i) I_i}{\sum_{pixels} W_g(\boldsymbol{x}_i) I_i}$$

$$W_g(\boldsymbol{x}_i) \equiv \exp\left[-\frac{1}{2}(\boldsymbol{x}_i - \boldsymbol{x}_c)^T {\boldsymbol{M}_g}^{-1}(\boldsymbol{x}_i - \boldsymbol{x}_c)\right]$$

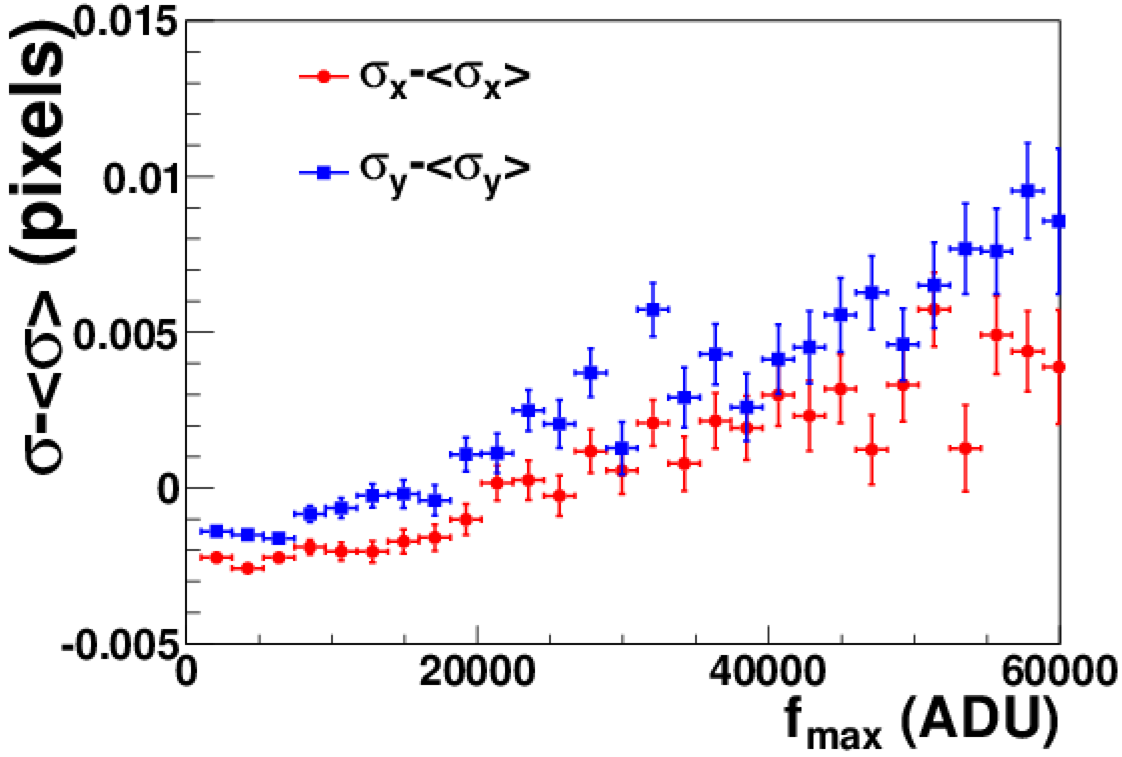
I_i : sky-subtracted image

We have checked that, even with a non-Gaussian PSF, the recovered size is independent of flux when PSF size is independent of flux.

The brighter-fatter effect

- The source of the effect has to be non-linear.
  - If it where linear, shape would not change with flux.
  - It hence cannot be due to diffusion.
- Non-linearity of overall response ?
  - Obviously possible
- What about other sensors?

The effect also shows up on MegaCam (@CFHT)...



Chips : E2V CCD42-90
(thinned chips)

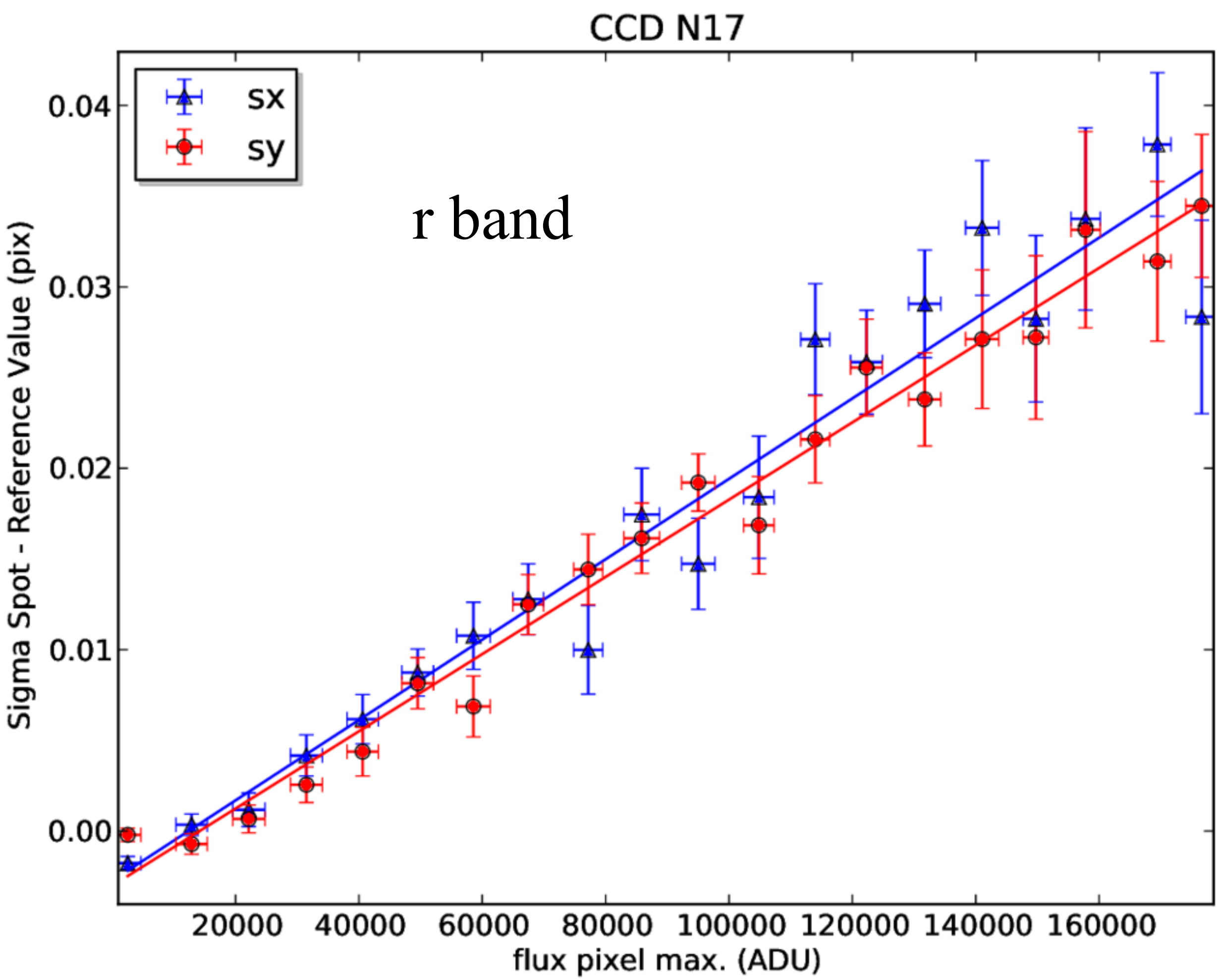
(CFHTLS data)

Less than 0.5% over the whole range.

And it is pretty much achromatic

(SNLS photometry technical paper, A&A 557, A.55 2013)

… and on DECam (@CTIO-4m)



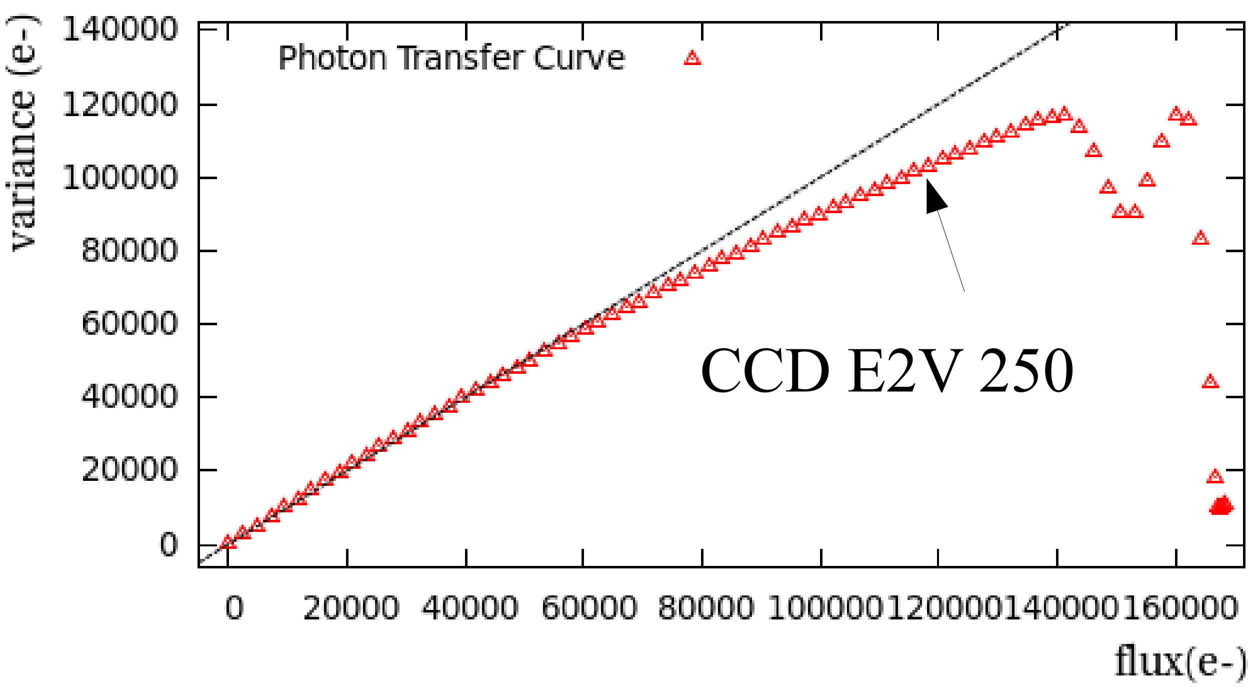
LBL/DALSA chips
high-rho
250 µm thick

Measurements from
Science Verification
Data (i.e. on sky)
with a tiny
color correction

Other strange effects on CCDs (1)

Variance of flat fields is not exactly proportional to their average

Photon Transfer Curve (PTC) :
variance=f(average)



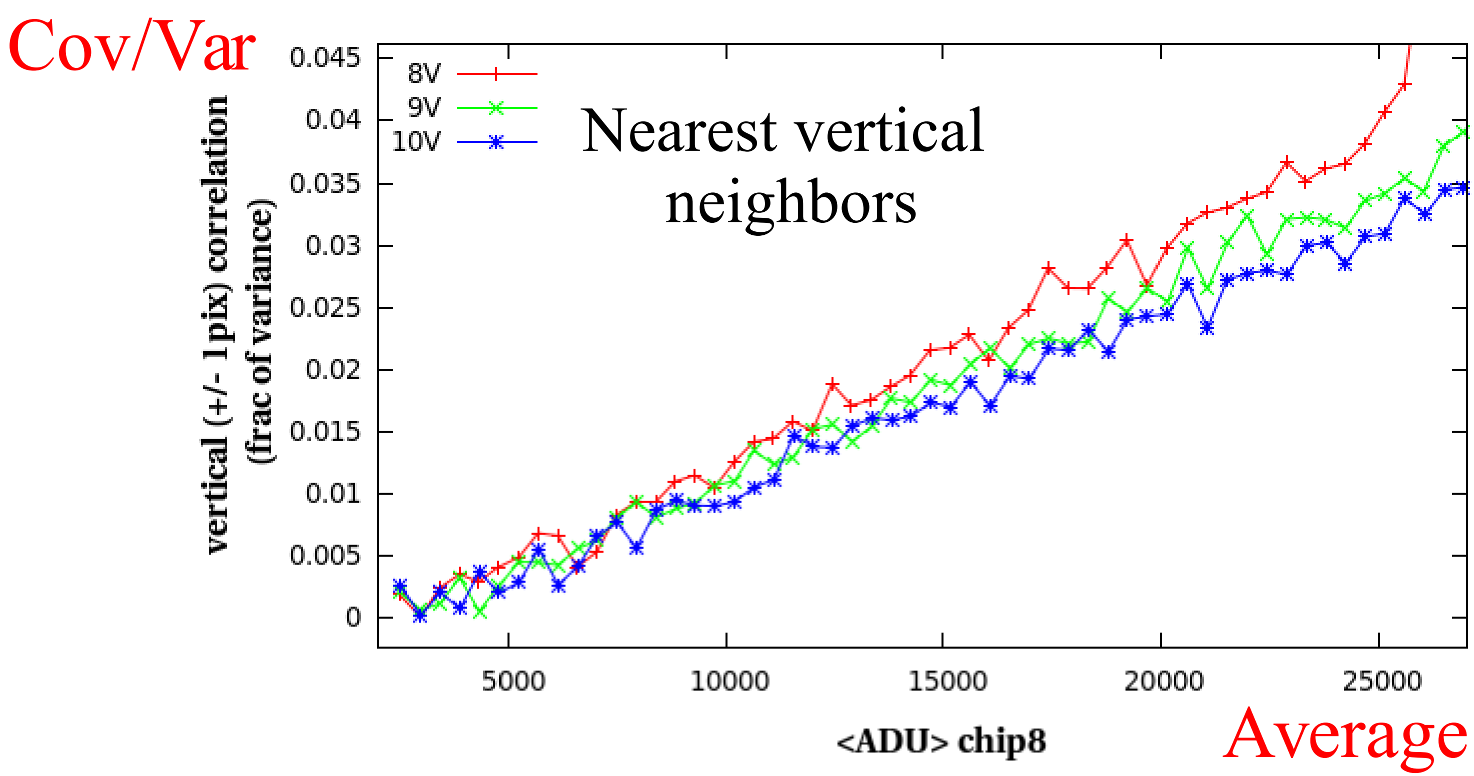
??

Siméon Denis Poisson

Non-linearity of PTC tends to go down when re-binning the image.

Other strange effects on CCDs (2)

Flat-field pixels are not statistically independent.
Their correlations increase (linearly) with illumination.



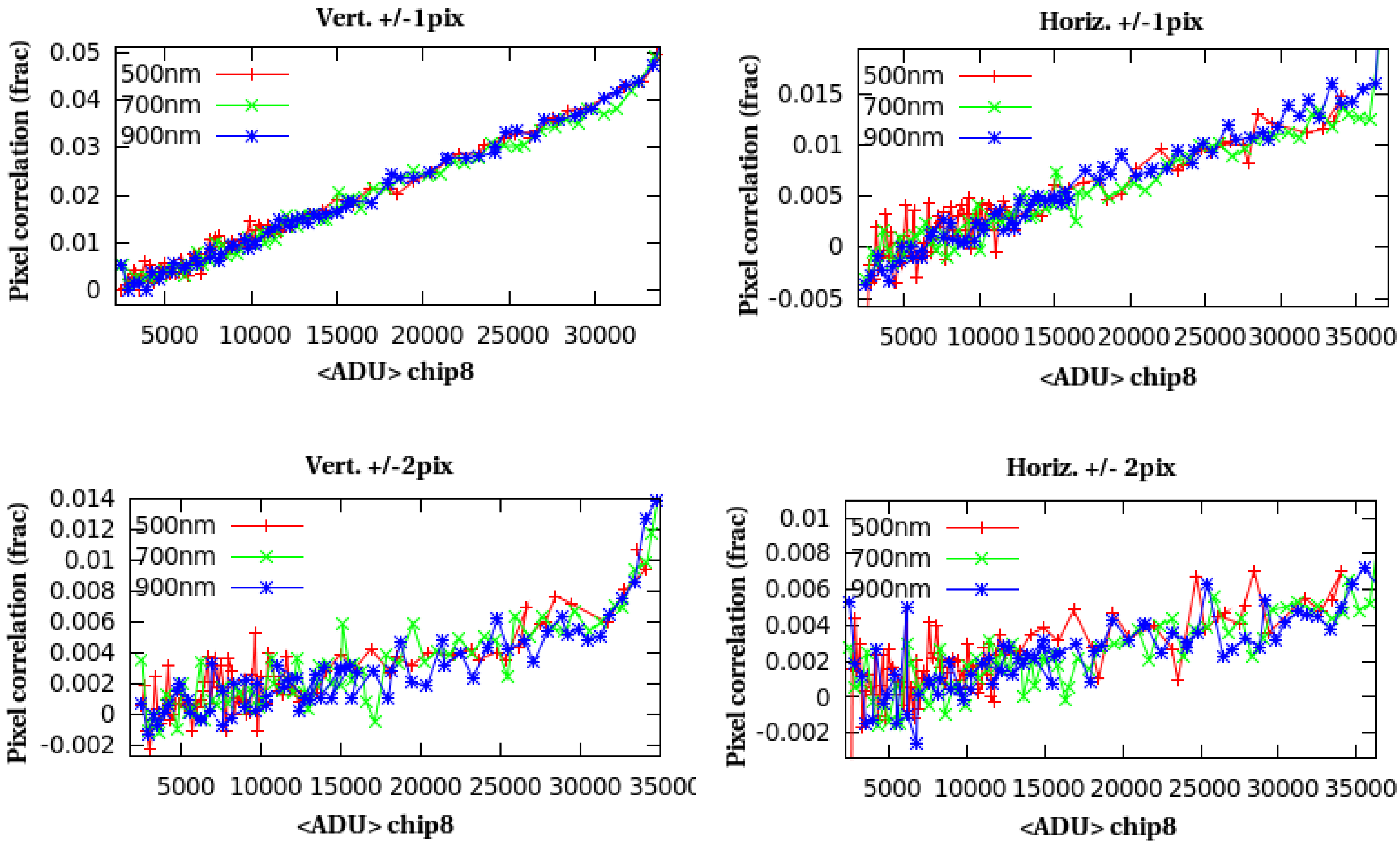
- E2V CCD

-Measurements by P.Doherty (Harvard)

-Analysis by A. Guyonnet (Paris)

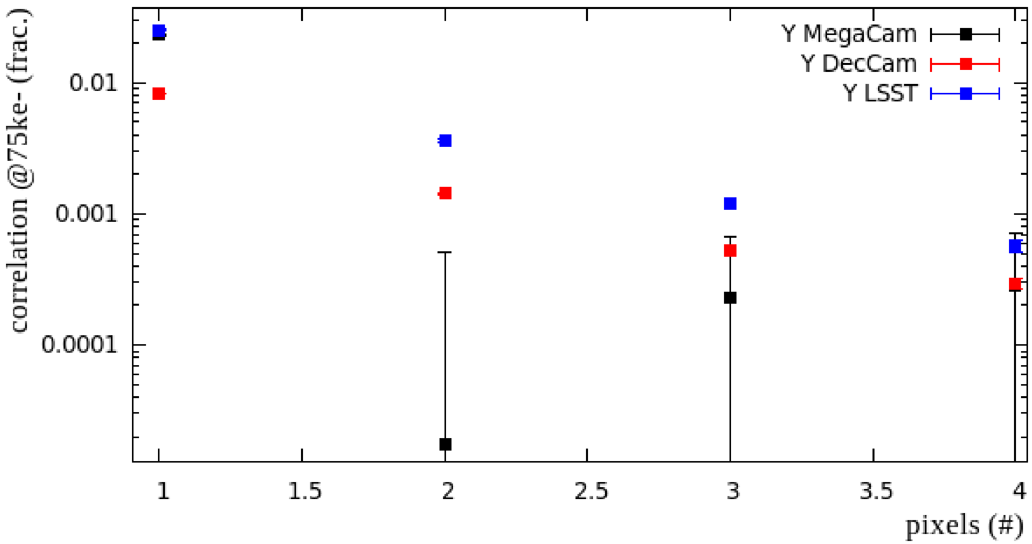
- Linear increase with flat-field average
- Depends on some electrostatic boundary condition.

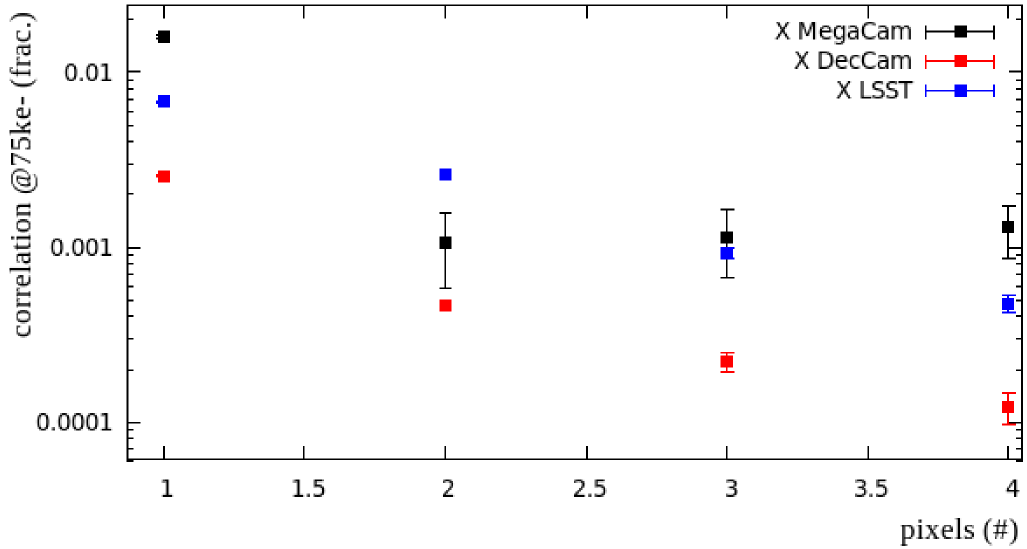
These correlations seem to be achromatic



So, the effect does not depend on how deep photons convert.

These correlations decay with distance





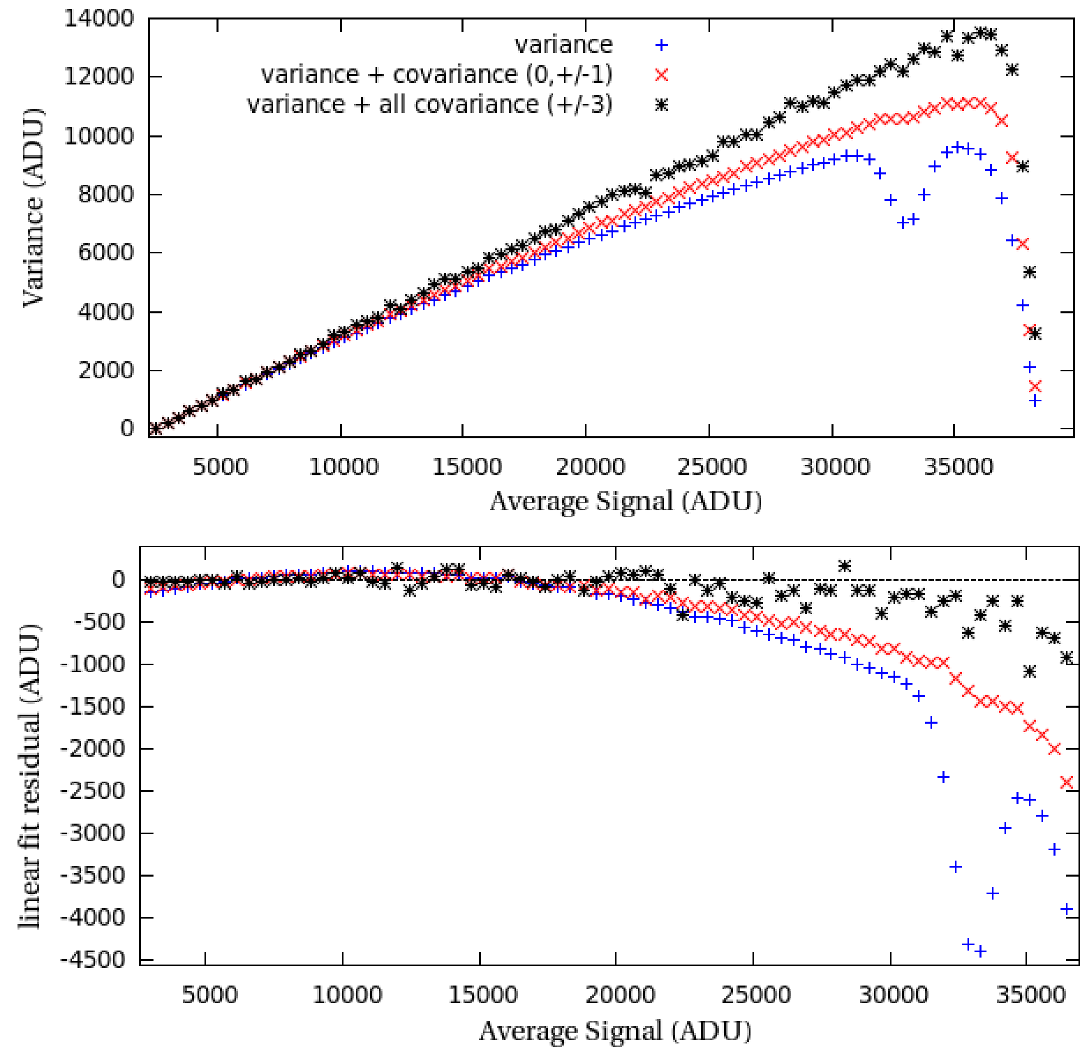
- correlations decrease roughly exponentially with separation.

- They are larger along Y than along X.

Non-linear PTC and correlations

Unsurprisingly, when accounting for pixel correlations, the PTC becomes more linear

PTC for ccd e2v 250



About non-linearity of PTC

With correlations increasing linearly with illumination, we have:

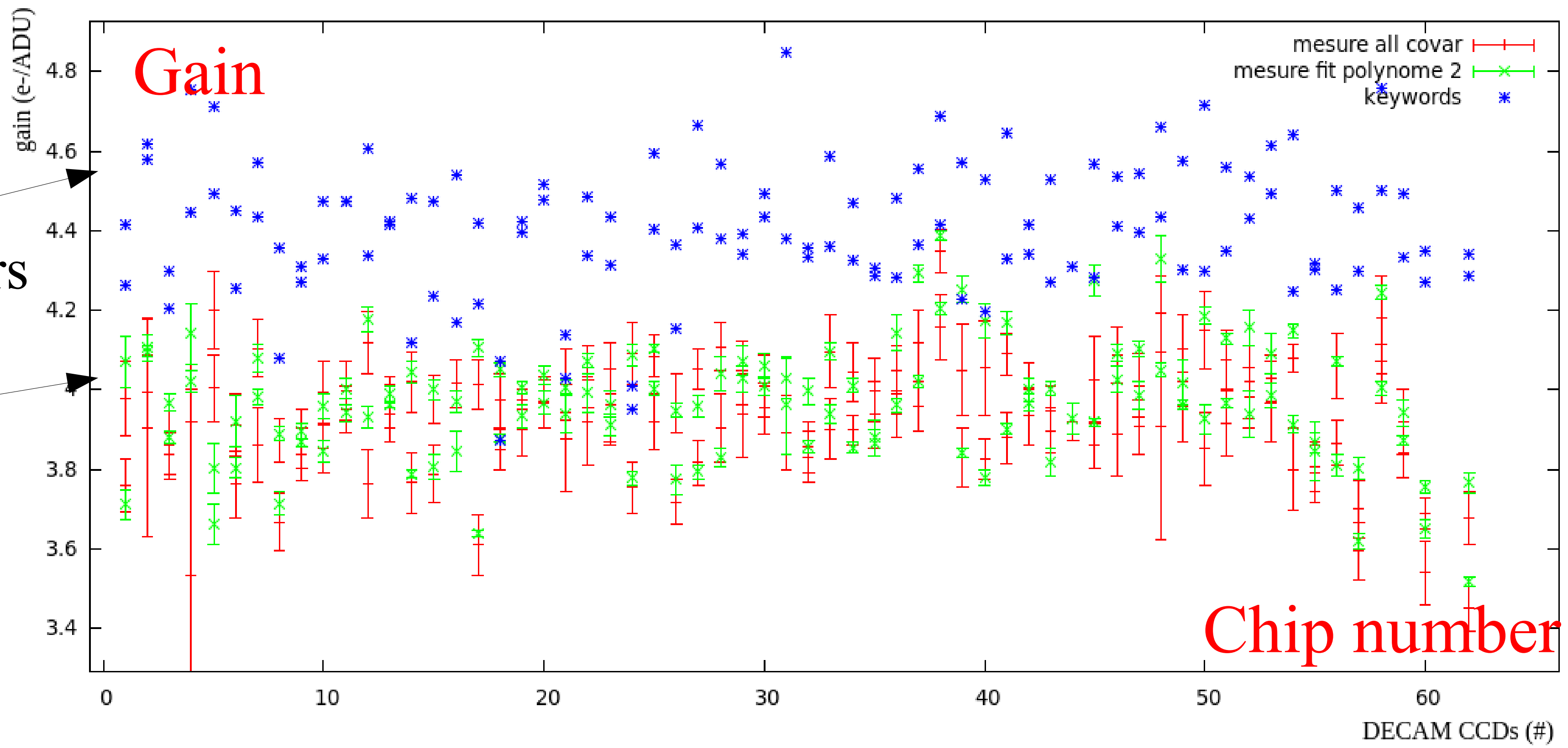
$$V = a\mu^2 + b\mu + c$$

a : correlations
b = 1/Gain
c : readout noise

DECam Science Verification data

Values in FITS headers

Parabolic fit to PTC



P. Astier PACCD (2014)

So,

We detect 3 effects :

- brighter-fatter for stars/spots
- Variance of flatfields is smaller than Poisson
- Flatfields exhibit correlations

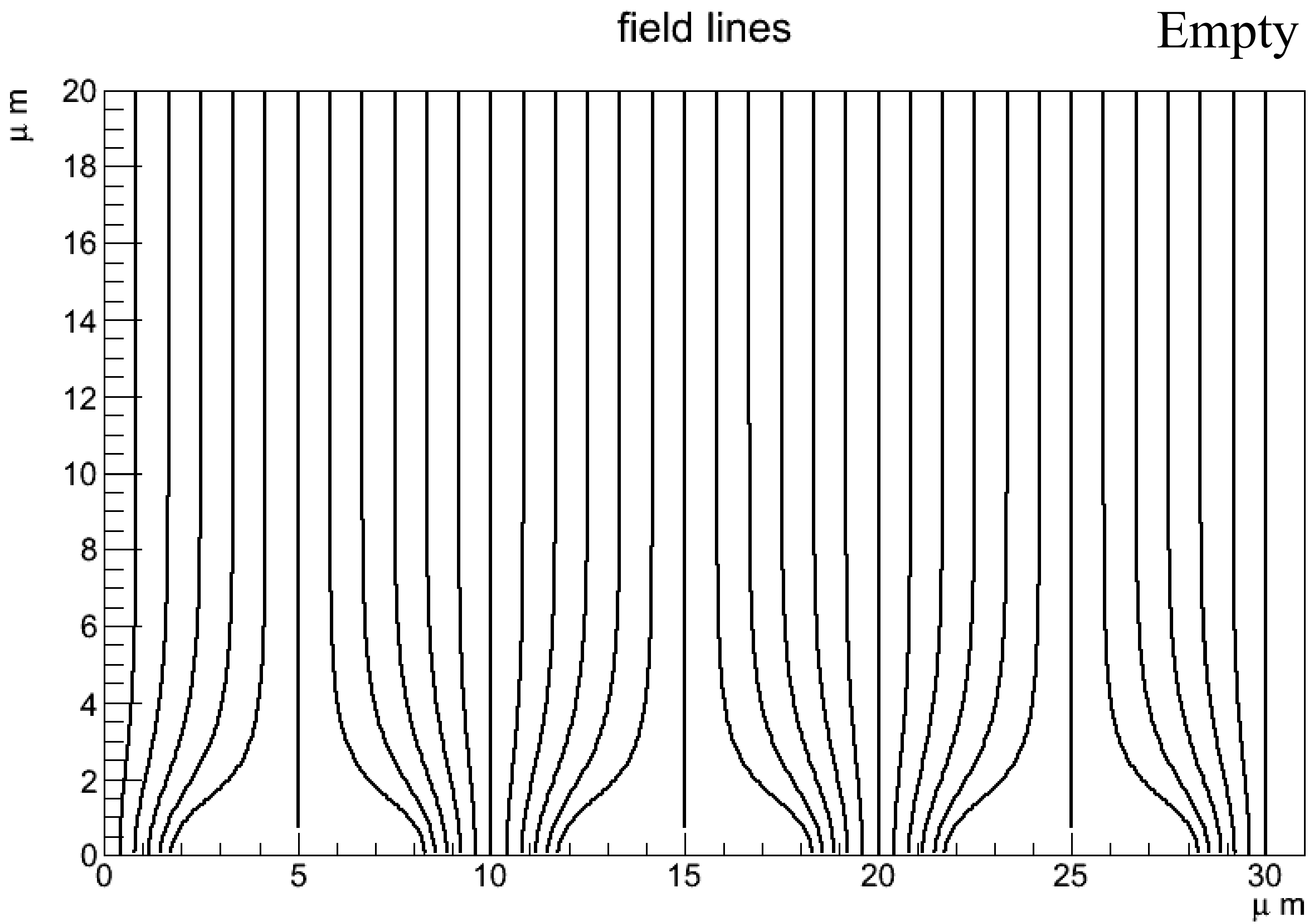
Linearly increasing with illumination.

- The two last effects are trivially related.
- Smoothing of flatfields and stars might share the same origin.

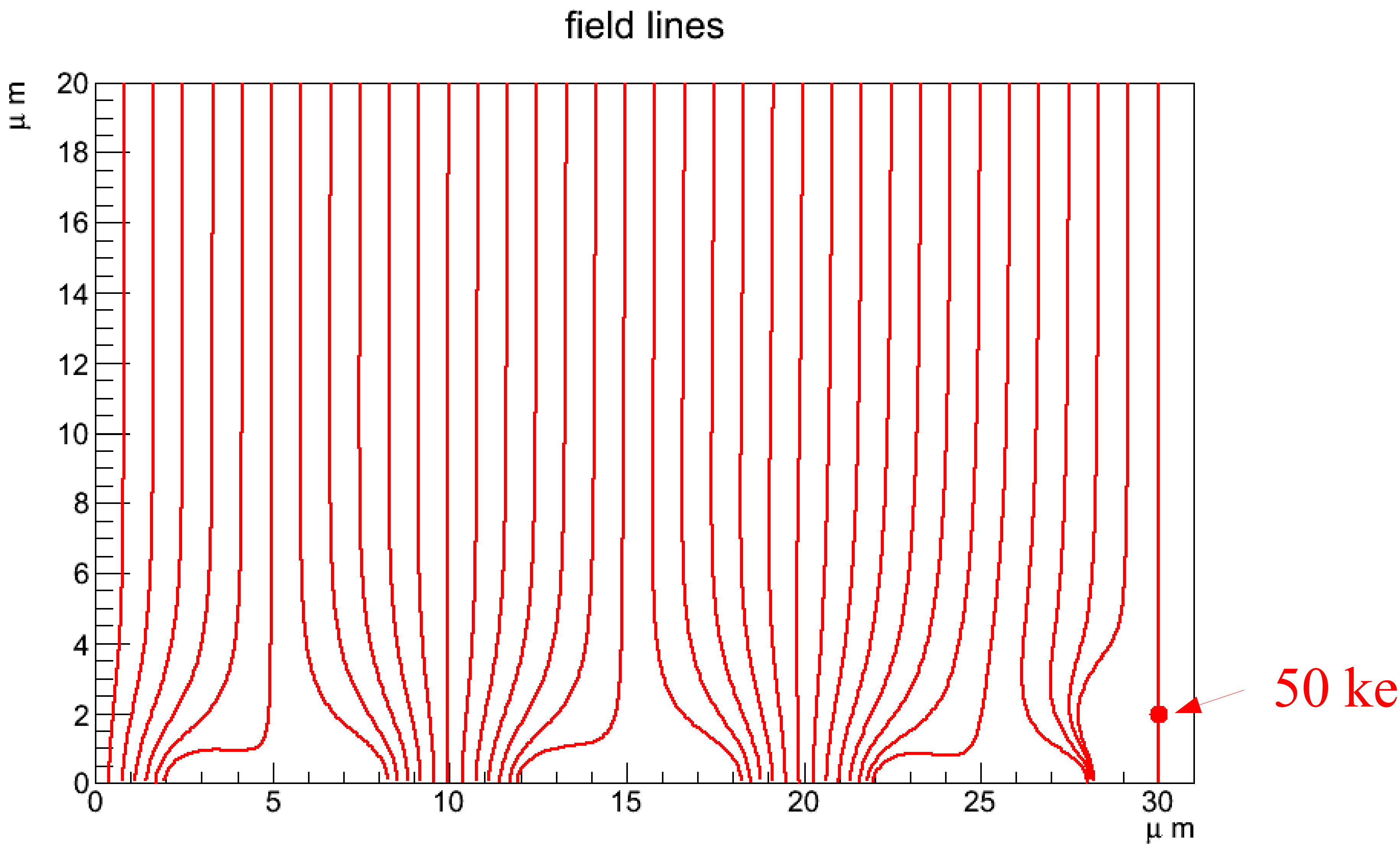
All 3 effects require some non-linear mechanism

Coulomb forces in a CCD

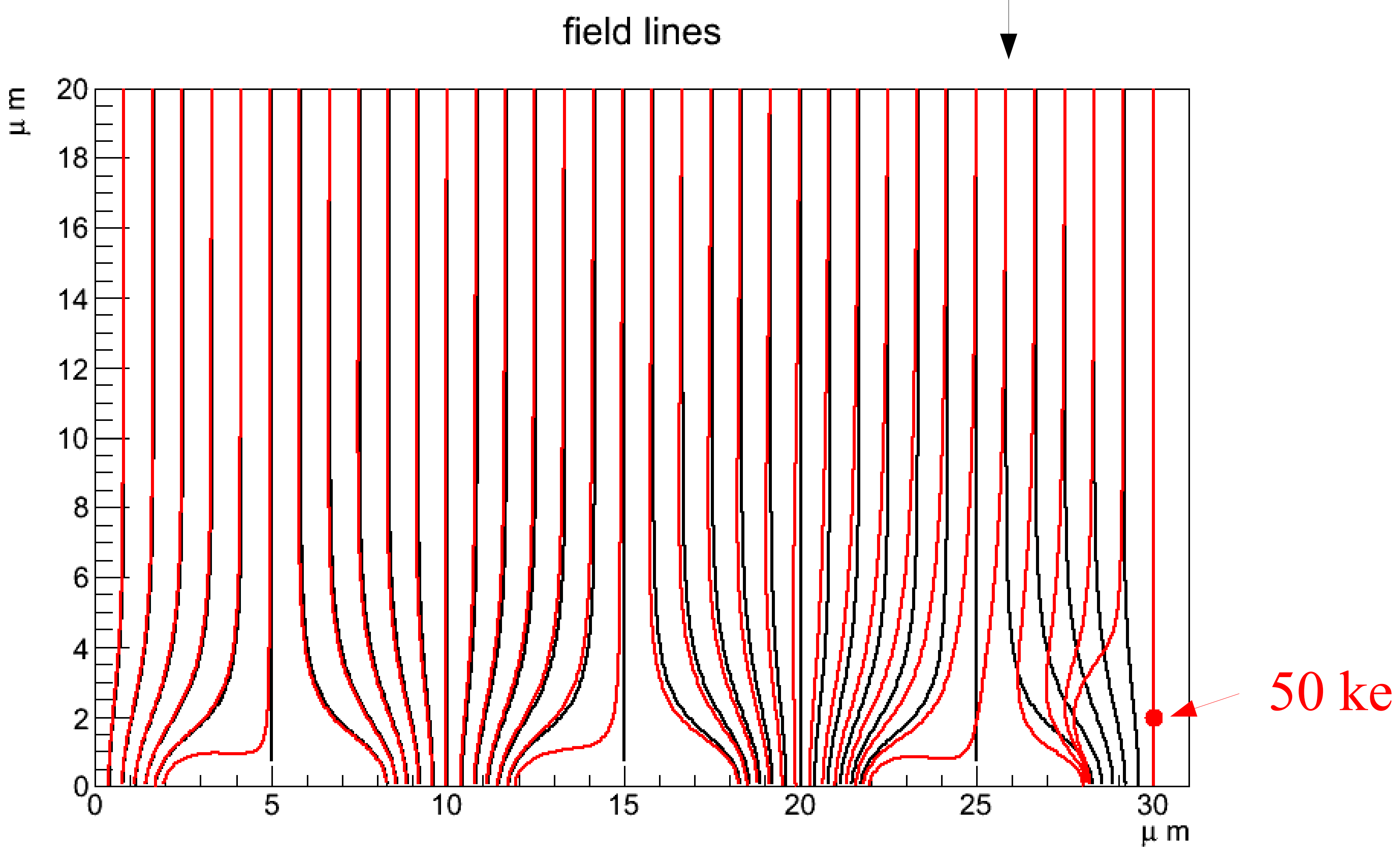
Empty CCD



Coulomb forces in a CCD

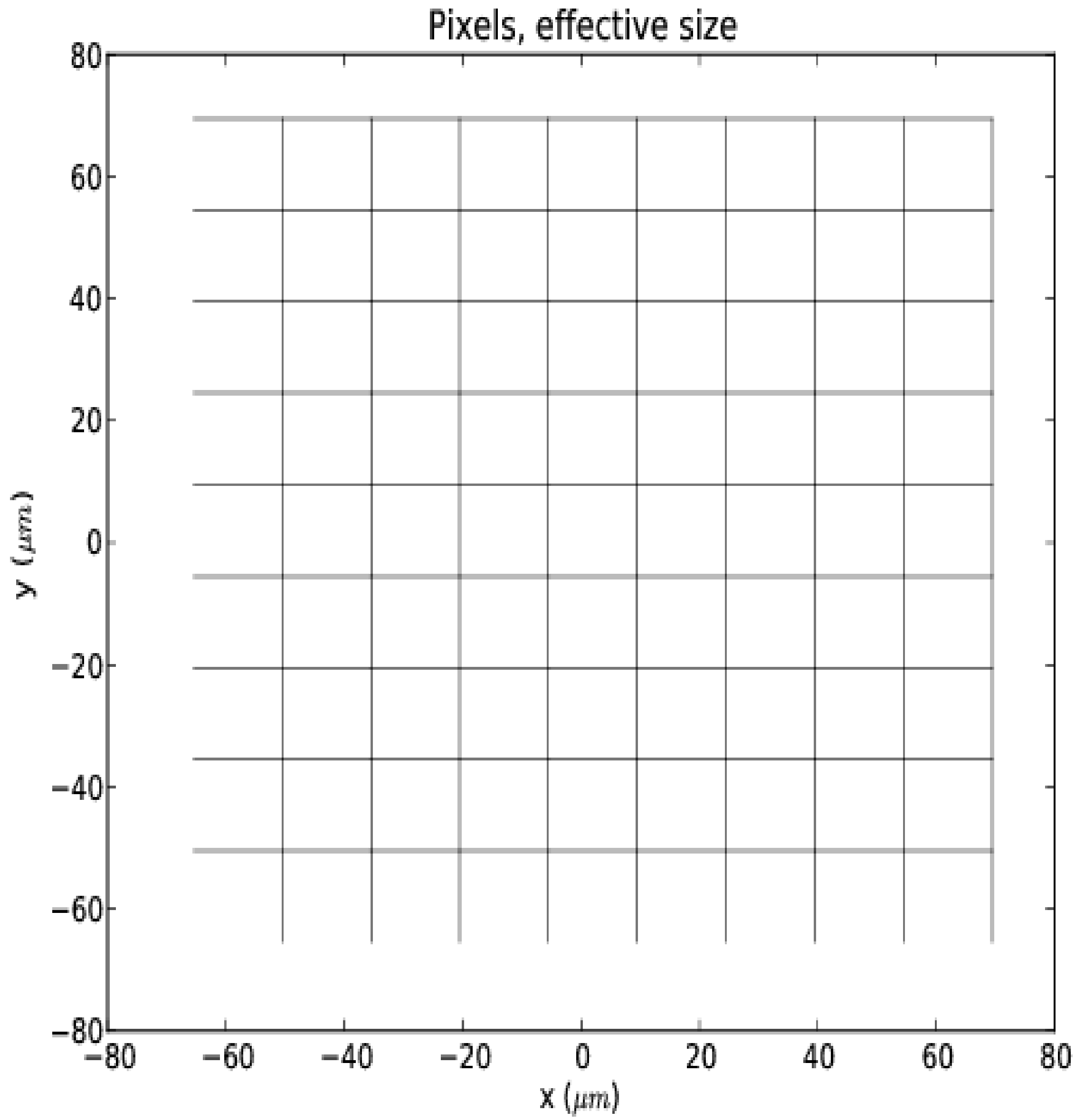


Depending on the stored charge, electrons drifting here go left or right



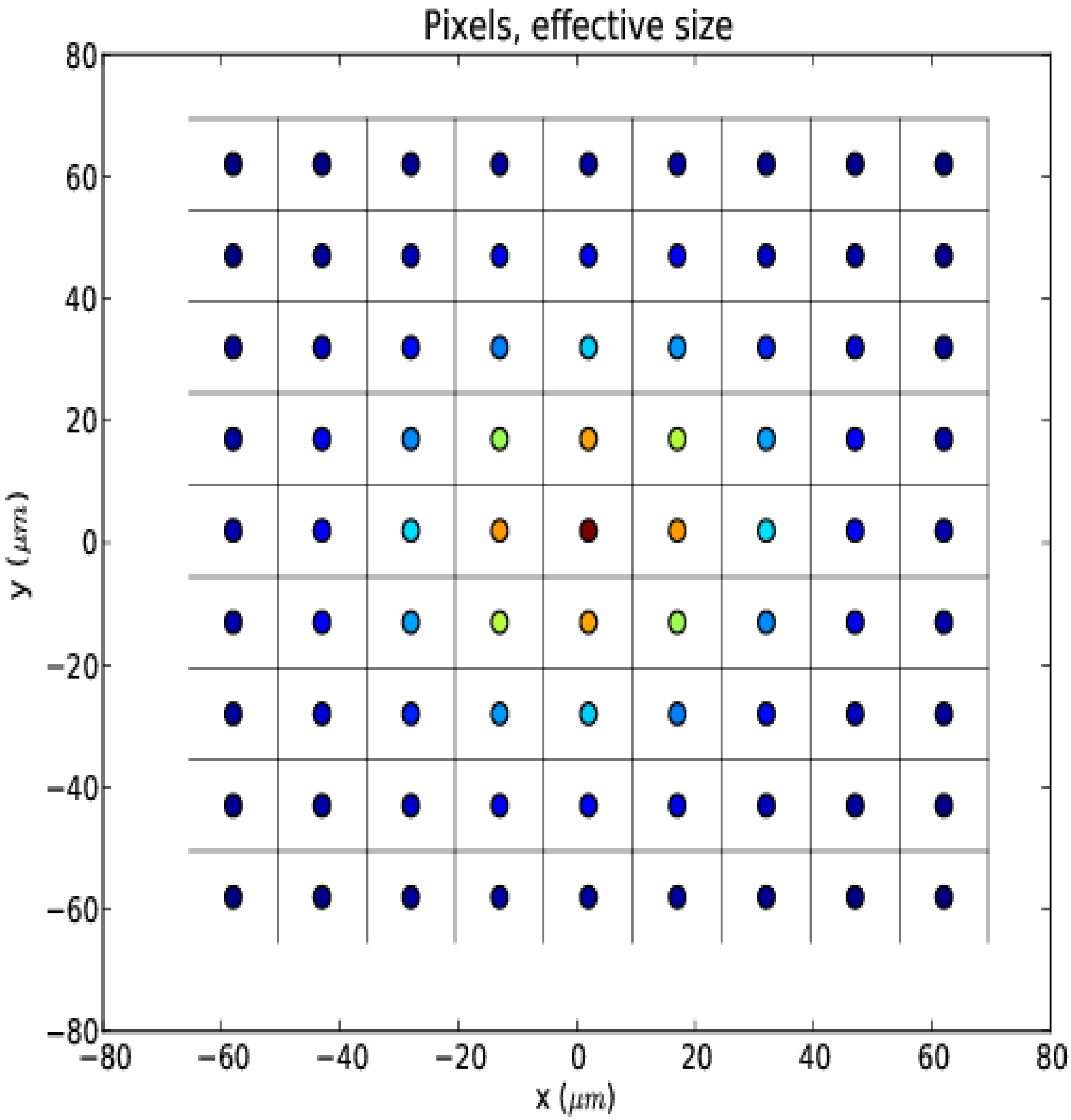
Top view

Empty CCD



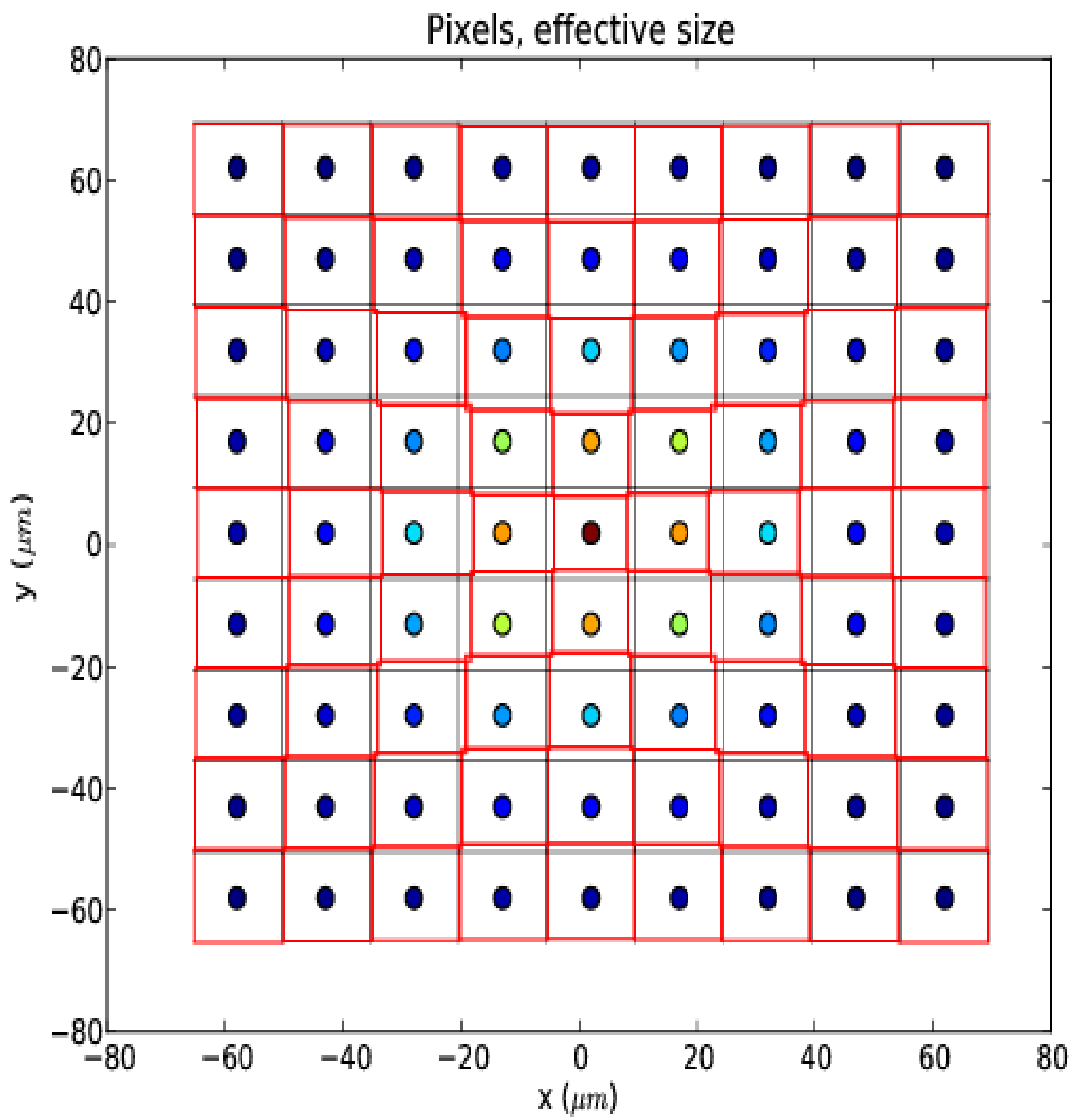
Top view

Add a bright star



Top view

Shifted pixel boundaries (shifts x 5)



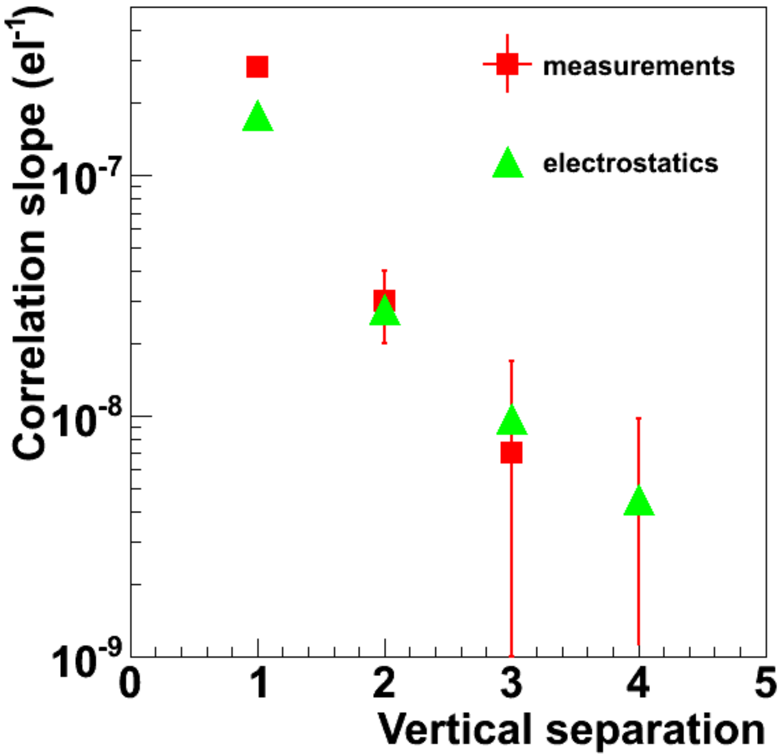
So,

Due to Coulomb forces, overfilled pixels get smaller w.r.t the average pixel size. This effect:

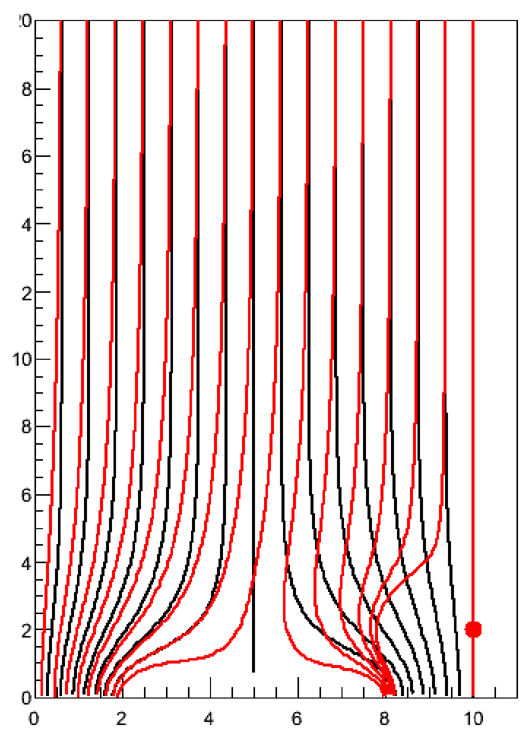
- Reduces spatial variance of flat-fields w.r.t Poisson
- Causes positive correlations in flat fields (sourced by Poisson fluctuations)
- Broadens bright spots w.r.t fainter ones

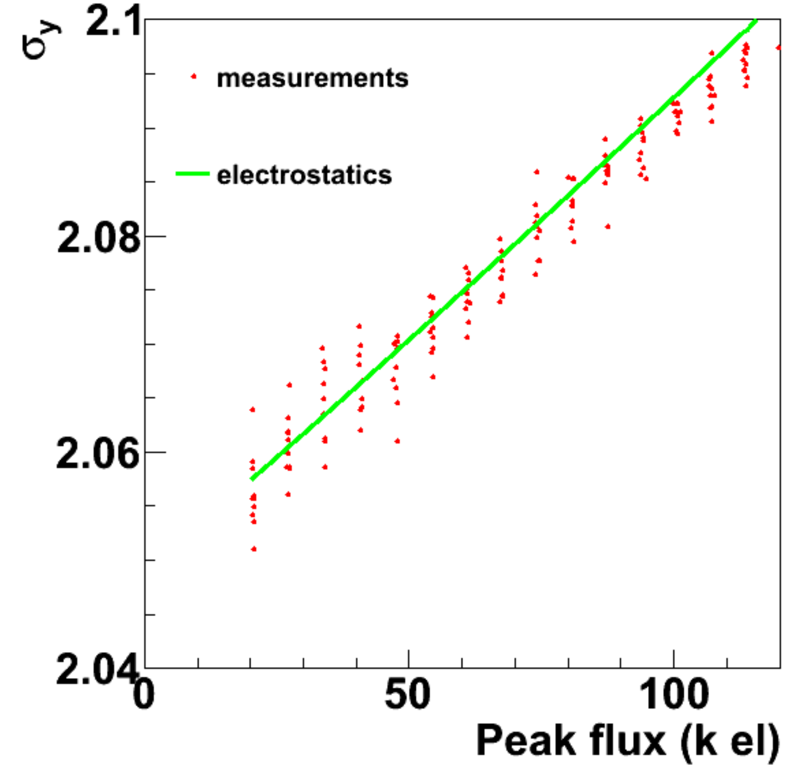
Charles-Augustin de Coulomb

Can Coulomb forces cause the observed size of effects ?



E2V CCD





A sketchy simulation roughly reproduces the size of the observed correlations and of the brighter-fatter slope.

An empirical model

- We do not know the details of how CCDs are made
- Most vendors would not answer our questions.
- The effect is small and hence Taylor expansions should hold
- Rather than making quantitative predictions from electrostatics, we make a general first order model and (try to) derive its unknowns from data.

Do the brighter-fatter effect and flat-field correlations share the same origin ?

TEST:

$$Q'_{0,0} = Q_{00} + \sum_X \sum_{ij} a_{ij}^X Q_{ij} (Q_{00} + Q_X)$$

Derive coefficients from flat-field correlations

$$Cov(Q'_{00}, Q'_{ij}) = 4 \mu V \sum_X a_{ij}^X$$

Scramble faint spots (or stars) and compare to bright ones

Distortions without assuming good sampling

Assumes the image is well sampled.

Pixel level:

$$\delta Q_{0,0} = \sum_X \sum_{ij} a_{ij}^X Q_{ij} (Q_{00} + Q_X)$$

Source charge

Test charge.

Correction to PSF model:

$$\delta Q_{0,0} = \sum_X \sum_{ij} a_{ij}^X Q_{ij} \times flux \times PSF((x_{00} + x_X)/2)$$